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FLUIDIZED BED CLARIFICATION AS APPLIED TO WASTEWATER TREATMENT

John C. Orcutt

Research Triangle Institute

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Fluidized Bed Clarification as Applied to Wastewater Treatment

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FLUIDIZED BED CLARIFICATION AS APPLIED TO WASTEWATER TREATMENT,

Orcutt, J. C.

EPA Program
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Environmental Protection Agency, ~~Washington, D. C.~~ Cincinnati, Ohio, ~~Office of Research and Monitoring~~ Advanced Waste Treatment Research Laboratory.

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In order to determine the effects of controlled process variables on the treatment achieved, an experimental study was made of the application of the fluidized sludge blanket clarifier to the coagulation and separation of wastewater solids. Systematic variation of wastewater pH, coagulant dose, upflow velocity and blanket depth was conducted in experiments using alum and ferric chloride coagulants. Regression analysis techniques were used to analyze the results and empirical relationships were derived relating the variables to the removal of suspended solids, total organic carbon, phosphorus, and coagulant metal ions. The operating variables were used to perform an empirical correlation with the sludge production rate. Both alum and ferric chloride were found to be effective coagulants. Although, best removal efficiencies were achieved at lower rates, the sludge blanket acted as an efficient clarifier up to at least 15 feet per hour superficial velocity. (Smith-Texas)

*Coagulation, *Analytical techniques, *Chemical precipitation, *Waste water treatment, Waste treatment, Separation techniques, Flocculation, Water treatment, Sewage treatment, Activated sludge, Sludge, Alum , Suspended solids, Mathematical studies,

Hydrogen ion concentration , Clarifier blanket, Removal efficiencies

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EPA-R2-72-032
December 1972

FLUIDIZED BED CLARIFICATION

AS APPLIED TO WASTEWATER TREATMENT

By

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ABSTRACT

An experimental study of the application of a fluidized sludge blanket clarifier to the coagulation and separation of wastewater solids has been made to determine the effects of controlled process variables on the treatment achieved.

Experiments using alum and ferric chloride coagulants were carried out in 12- and 24-inch diameter columns by systematic variation of wastewater pH, coagulant dose, upflow fluid velocity, and blanket depth. The results were analyzed using regression analysis techniques, and empirical relationships were derived relating the variables to the removal of suspended solids, total organic carbon, phosphorus, and coagulant metal ions. The sludge production rate was also correlated empirically with the operating variables.

A study of the settling rates of discharged sludge and the fluidized blanket was made by direct observation.

Both alum and ferric chloride were found to be effective coagulants. The sludge blanket acted as an efficient clarifier up to at least 15 ft/hr superficial velocity, although best removal efficiencies were achieved at lower rates.

This report was submitted upon fulfillment of Contract 14-12-912 under the sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

Key words: sludge blanket clarifier, upflow clarifier, sewage treatment, solids removal, TOC removal, phosphorus removal.

CONTENTS

Section		Page
I	Conclusions	1
II	Recommendations	3
III	Introduction	5
IV	Equipment	7
V	Experimental Procedure	17
VI	Experimental Design	21
VII	Results and Discussion of Experiments Using Alum	25
VIII	Results and Discussion of Experiments Using Ferric Chloride	49
IX	Sludge Settling Studies	61
X	Experiment Using Activated Silica as a Sludge Thickening Aid	77
XI	Acknowledgments	79
XII	References	81
XIII	Publications and Patents	83
XIV	Appendices	85

FIGURES

		Page
1	12-Inch Diameter Lucite Column	8
2	24-Inch Diameter Fiber Glass Column	9
3	System Flow Diagram	13
4	Photograph of Columns	14
5	Photograph of Mix Tank	15
6A	Suspended Solids in Effluent	28
6B	Suspended Solids in Effluent	29
7	Total Organic Carbon in Effluent	32
8A	Soluble Phosphorus in Effluent	34
8B	Soluble Phosphorus in Effluent	35
9A	Total Phosphorus in Effluent	36
9B	Total Phosphorus in Effluent	37
10A	Residual Aluminum in Effluent	41
10B	Residual Aluminum in Effluent	42
11	Sludge Production	45
12	Suspended Solids in Effluent	50
13	Total Organic Carbon in Effluent	51
14	Soluble Phosphorus in Effluent	52
15	Total Phosphorus in Effluent	53
16	Residual Fe^{+++} in Effluent	54
17	Settling Curve for Blanket of Test Run A1	62
18	Settling Curve for Sludge of Test Run A1	63
19	Flux Curve	72
20	Sludge Settling Rates vs. Suspended Solids Concentration	73
21	Reciprocal Minimum Solids Flux vs. Thickener Solids Concentration	76

TABLES

		Page
1	Analysis of Raw, Degritted Wastewater Influent	19
2	Effect of Alum Dose on Influent pH	30
3	Summary of Regression Analysis of Experimental Data Using Alum	46
4	Summary of Predicted Treatment Effects Using Alum	47
5	Summary of Regression Analysis of Experimental Data Using Ferric Chloride	55
6	Summary of Predicted Treatment Effects Using Ferric Chloride	58
7	Data of SS from the Upflow Clarifier	66
8	Observed Parameters of the Clarifier	68
9	Observed Parameters of Sludge Tests	70
10	Treatment Effects Using Alum with Activated Silica	78

SECTION I

CONCLUSIONS

The following major conclusions may be listed:

a) Treatment Effects. The sludge blanket clarifier using either alum or ferric chloride is an effective means for removing the major contaminants from wastewater. Although there is some advantage in a smaller sludge yield using ferric chloride, the residual Fe^{+++} in the effluent may make its use less desirable than alum. The major variables affecting treatment results were found to be pH, coagulant dose, blanket depth, and upflow velocity, with considerable interactions existing between these variables. Column diameter was not found to have a significant effect within the size range studied.

b) Application of the Correlations. The empirical nature of the study and the resulting correlations do not allow conclusions to be drawn relating to the mechanisms of sludge blanket clarification. Moreover, the variability of unknown constituents in the wastewater continually shifts the conditions of optimality.

c) Sludge Production. Minimum sludge production can be achieved by proper choice of coagulant dose and operating conditions. The use of activated silica with alum caused a marked thickening of the sludge, and its use is indicated as an additional means of reducing sludge volume.

d) Sludge Thickening. Sludges produced during alum treatment exhibited settling curves in which settling rates were significantly dependent upon solids concentration. The settling rate of the sludge blanket, however, was found to be no different than the upflow velocity.

SECTION II

RECOMMENDATIONS

The following recommendations may be made:

a) A study should be made to determine means of reducing the sludge production. Both the effects of thickening agents and special clarifier mechanical design should be considered.

b) A study should be made to establish methods of instrumentation and control of a sludge blanket clarifier so that optimal treatment conditions are maintained during periods of changing influent. The dynamics of influent smoothing should be considered concurrently.

c) A study of further effluent treatment should be carried out to assess the full potential of the sludge blanket clarifier in an integrated physical-chemical treatment facility.

d) A large-scale design study by an experienced engineering firm should be made to establish construction and operating costs.

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SECTION III

INTRODUCTION

Suspended and colloidal solids can be effectively removed from raw sewage by treatment with a coagulant followed by solids separation. Traditionally, chemical treatment has been by agitation (rapid mixing) followed by slow mixing (flocculation) and sedimentation. In the design of such systems, the major problem is to achieve the proper time-concentration-shear relationships in the mixing step so that an easily separated floc is obtained.

An alternative method of chemical treatment is by use of the fluidized blanket clarifier. This method seems to have wide use in Europe, but in this country it is primarily used in water softening plants. The history of the upflow clarifier appears to date from the late 19th Century. The first large-scale application was in 1880 in the city of Dortmund, Germany. Numerous patents have since been granted, and several commercial models are currently available.

The fluidized sludge blanket clarifier (FSBC) has a size advantage over the conventional system because the floc-supernatant separation occurs in the same vessel used for the flocculation. The vessel cross-sectional area required to handle equal flows can be as much as one-third less for the FSBC than a conventional clarifier.

The sludge production rate from a fluidized sludge blanket clarifier may be much greater than from a conventional settler unless adequate thickening area is provided. If an additional thickening vessel is required, some of the initial size advantage over the conventional process may be lost, but in terms of total capital investment the cost may be less if the sludge has better settling characteristics.

Culp and Culp (6) state that field experience indicates surface overflow rates for clarifiers for the removal of floc from chemically treated sewage must be less than those recommended for water treatment to prevent excessive floc carryover. They also state that maintenance of sludge blankets in upflow clarifiers has proved difficult in sewage treatment applications. The results of this present study suggest this to be not always true.

The present study has been made to assess the effectiveness of the FSBC in the chemical treatment of raw sewage by performing experiments in which the operating variables were changed in a planned way and changes in treatment observed. Alum and ferric chloride were used as coagulating agents, and the effects of pH, coagulant dose, fluid velocity, blanket depth, and column diameter were measured as they affected the removal of TOC, phosphates, suspended solids and coagulant metal ions. Additional studies were made to examine the settling behavior of the blanket and of the sludge produced.

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The approach taken in studying the effects has been largely phenomenalistic. That is, the forms of the relationships between causes and effects have been deduced by statistical methods in an attempt to reduce the unaccountable variation in observations. Although municipal wastewaters vary considerably in quality, these data should be applicable to many municipal plants which receive a predominantly domestic waste.

SECTION IV

EQUIPMENT

Four clarifier columns were used; two were 12-inch diameter transparent Lucite, and two were 24-inch diameter reinforced translucent Fiberglas. All columns were built as an 8-foot straight section with a flanged top section. The top sections were 1 and 2 feet tall for the 12-and 24-inch columns, respectively. Threaded taps were located at intervals in the wall of the 8-foot section for blanket sampling. The columns are depicted in Figures 1 and 2.

Column Design

12-inch Diameter Lucite Columns. The 12-inch columns had 60° conical sheet metal bottoms flanged to the main section with 3-inch standard threaded unions brazed to the bottom to receive the flow distributor and sludge removal fittings. Liquid overflow from the top of the column was removed over an annular weir through the column wall. The weir was fabricated of Fiberglas and flanged between the top and middle column sections. Use of the weir assured a constant liquid level in the column during normal operation.

The wastewater was introduced into the column through a single 1-inch copper pipe which extended vertically to the level of the bottom flange. A circular copper plate 2-1/2 inches in diameter was mounted at 90° to the flow 1 inch directly above the pipe opening. This plate acted as a baffle and forced the incoming liquid to flow radially outward. The purpose was twofold:

1) to prevent direct upward jetting and destruction of the blanket

2) to provide additional turbulent mixing for the coagulant and the wastewater feed.

The position of the open end of the distributor at the flange level also prevented undesirable sludge accumulation which eventually would block the opening of the distributor. This was found to occur when the pipe was mounted lower in the conical column bottom.

The copper inflow pipe was mounted inside a 3-inch brass tee by means of a bushing. The tee was threaded to the union on the conical column bottom. Sludge from the column passed out the column through the remaining open end of the tee run, as shown in Figure 1.

Lever-handled brass ball valves were used uniformly throughout the system. These had the distinct advantage of being quick-acting and non-clogging.

The columns were erected on tripods fabricated from steel angle stock.

24-inch Diameter Fiberglas Columns. The 24-inch columns had 45° conical bottoms of Fiberglas with a 2-inch flanged nozzle for sludge removal.

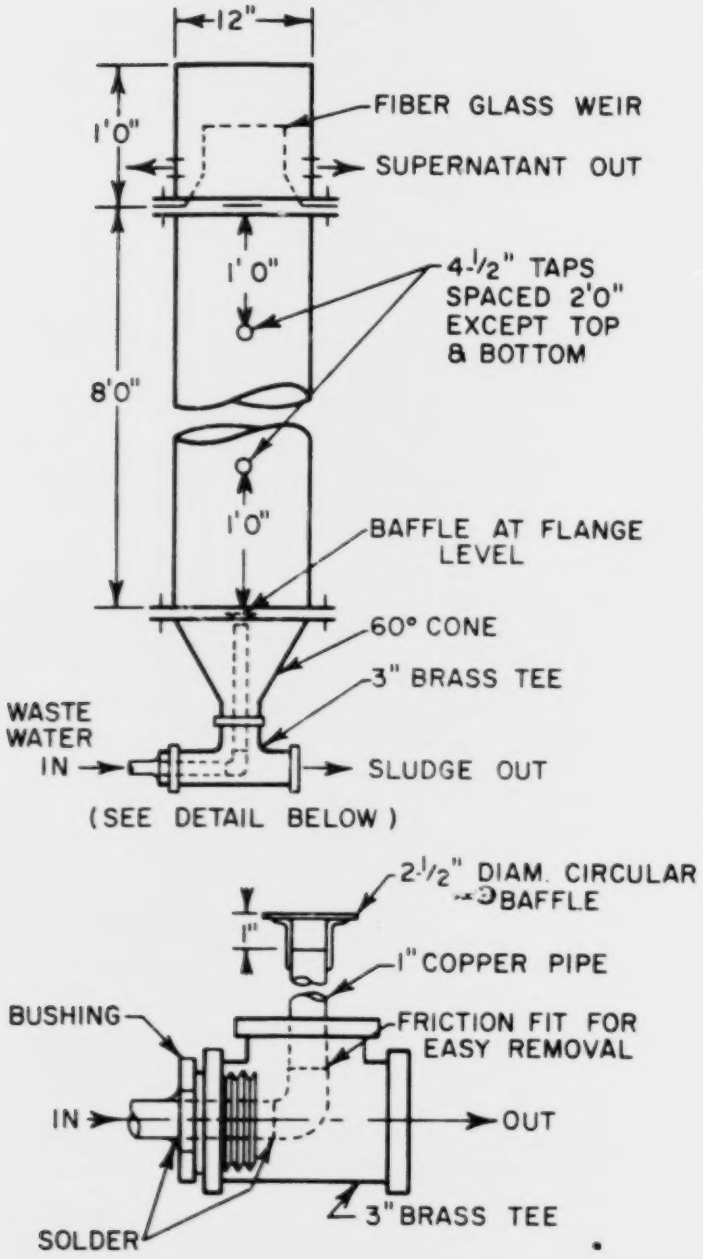


FIG. 1 12 INCH DIAMETER LUCITE COLUMN

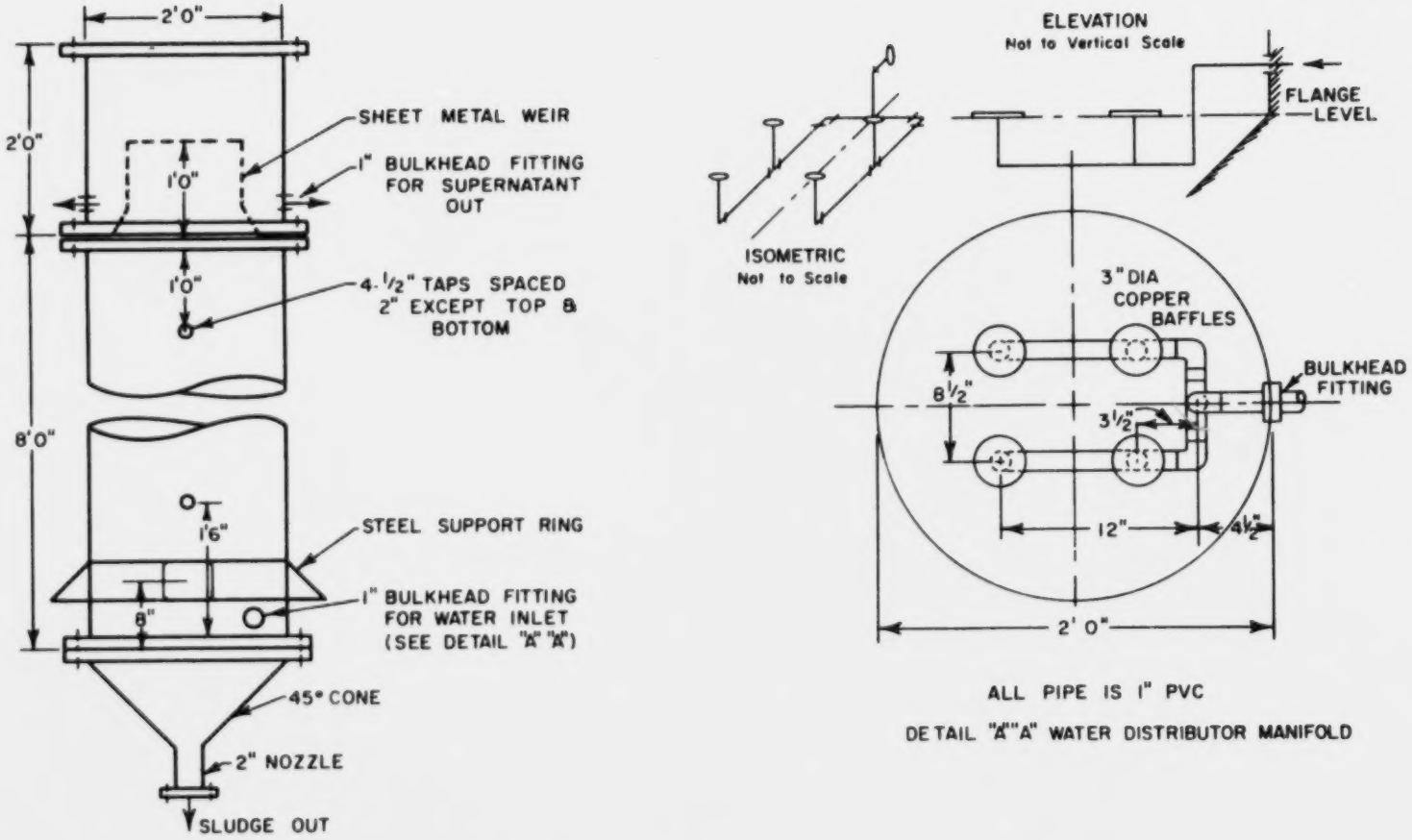


FIG. 2 24 INCH DIAMETER FIBER GLASS COLUMN

The conical bottom, as well as the 2-foot top section, was flanged to the 8-foot main section. Liquid overflow was removed over a sheet metal weir in the top section as in the smaller columns, as shown in Figure 2.

Because of the larger column cross-sectional area, the liquid was introduced through a 4-nozzle manifold built from 1-inch PVC pipe and fittings. Each vertical nozzle was fitted with a circular metal baffle as in the 12-inch columns, and they were arranged to discharge into equal fractions of the cross section. The tops of the nozzles were level with the cone-column flange. Liquid to the manifold entered through a single pipe through a plastic bulkhead fitting in the column wall about 2 inches above the flange rather than through the bottom of the cone as in the smaller columns. These details are shown in Figure 2.

Sludge Removal and Blanket Level Control

Initial attempts to control the blanket level by withdrawing sludge by means of an adjustable submerged weir were unsuccessful. It was soon found that the level of the blanket interface could be lowered by simply removing sludge from the bottom of the cone. This procedure was mechanized into a simple control system by using a photocell and a solenoid valve. The photocell was arranged to activate when the sludge blanket interface intercepted a light beam from the source to the cell. This caused a solenoid valve in the sludge withdrawal line to open, releasing sludge until the blanket level dropped to expose the cell to the light, causing the circuit to close the solenoid valve again. An adjustable timer was built into the circuit to delay activation of the solenoid valve so that random flocs or interface instabilities would not unnecessarily trigger the control. This system usually provided interface level control to within 1 inch or closer to the desired level, depending on the duration of the delay. Delay periods of up to 30 seconds were tried, but usually a shorter period of 10 to 15 seconds was adequate to prevent chattering of the valve.

The solenoid valves were Sears washing machine rubber diaphragm valves. These were eminently satisfactory, although with the slight disadvantage of being limited to about 2 feet of total fluid head to prevent rupture of the diaphragm. Accordingly, these valves were mounted at an elevation to keep the net head less than 2 feet. Actually, this arrangement also served as a safety device in preventing the complete loss of the column contents in case of photocell malfunction, since the total liquid level on the column could not drop below the level of the valve.

For the transparent 12-inch columns the photocell devices were made from inexpensive burglar alarm kits. These consisted of a light source which was mounted externally on one side of the column and a detector cell which was mounted externally on the opposite side. The light beam passing through the clear supernatnat liquid was intercepted by the upper surface of the sludge blanket and interrupted the signal. Since the Fiberglas column walls would not transmit sufficient light, this type of device could not be used with the 24-inch columns. For these columns commercial (Keene Corporation Model 8000 SCCS portable sludge level detector)

submersible photocell sludge level indicators were used. These were lowered directly into the blanket. The submersible cells operated best when a high intensity floodlight was mounted externally to provide sufficient illumination of the interface so that the photocell could detect the contrast between blanket and supernatant.

Flow Measurement

Owing to the surface-fouling nature of the wastewater, conventional rotameters were not indicated. Instead the total flow to each column was measured by timing the overflow in calibrated Lucite cylinders. These were mounted next to the columns with a ball valve manifold so that one cylinder could serve two columns. During flow measurement the photocells were disconnected so that the entire liquid flow passed overhead to the cylinder. The capacity of the cylinder serving the 12-inch diameter columns was 4.0 liters, while that serving the 24-inch columns was 8.0 liters.

The sludge removal rates were measured by timing the collection of the total amount discharged in 30-gallon plastic trash cans and weighing on platform scales.

Chemical addition flow rates were set by calibration of the adjustable chemical feed pumps.

pH Control

pH control was effected by using a Beckman Model 940 pH analyzer and electrode assembly. The electrode assembly consisted of a general purpose glass electrode, a LAZARAN™ process reference electrode, and a thermocompensator electrode. The electrodes were mounted in a plastic flow-through cell supplied by Beckman. No electrolyte is required when the LAZARAN electrode is used, a particular convenience in pilot plant operation. This system controlled the pH of the effluent from a 275-gallon mixing tank by pumping a solution of sodium hydroxide to the tank as required by the control point limits. A stream of tank effluent was recirculated continuously through the electrode cell supplied by the manufacturer. Initial experience showed that little fouling of the cell or electrodes occurred when the liquid rate through the cell was maintained at approximately 1 gallon per minute. Infrequent fouling by fibrous material did not appear to affect the controller accuracy. Calibration of the electrodes with standard buffer solution was made prior to each test run.

The degree of control achieved was at all times satisfactory, but with slight overshoot inherent to on-off systems. Deviations of $\pm$ 0.1 pH unit were normal.

Pumps

The feed was pumped to each column by flexible impeller pumps run with DC shunt wound motors operated by electronic speed controllers. The 12-inch columns were serviced by pumps having a capacity of about 2 gpm at

20 feet of head, while the 24-inch columns used larger pumps of about 8 gpm at 20 feet of head. One-third horsepower motors were found to be adequate.

The smaller pumps were marginally satisfactory. Although most of the larger grit had been removed from the wastewater by two 55-gallon drums, impeller abrasion occurred; and each impeller had to be replaced several times during the course of 6-months operation. No impeller failure occurred with the larger pumps.

It was discovered early that alum could not be added to the pump suction without causing severe impeller damage. Although this would have been better from the standpoint of mixing, the pumps had to be protected; and henceforward, alum was added at the pump discharge.

Raw sewage was pumped to the test site with a submersible centrifugal pump supplied by the treatment plant.

A system flow diagram is shown in Figure 3. Photographs of the equipment are shown in Figures 4 and 5.

Chemicals

Commercial-grade aluminum sulfate, ferric chloride and sodium hydroxide were used in these tests. The aluminum sulfate was found to have a composition consistent with the hydrated molecule $Al_2(SO_4)_3 \cdot 16H_2O$. This was determined from the aluminum content of a solution made by dissolving an accurate weight of the crystals in distilled water. Manufacturer's (Fisher Scientific) specifications list the ferric chloride as $FeCl_3 \cdot 6H_2O$. Sodium hydroxide was obtained in flake form for easy dissolution.

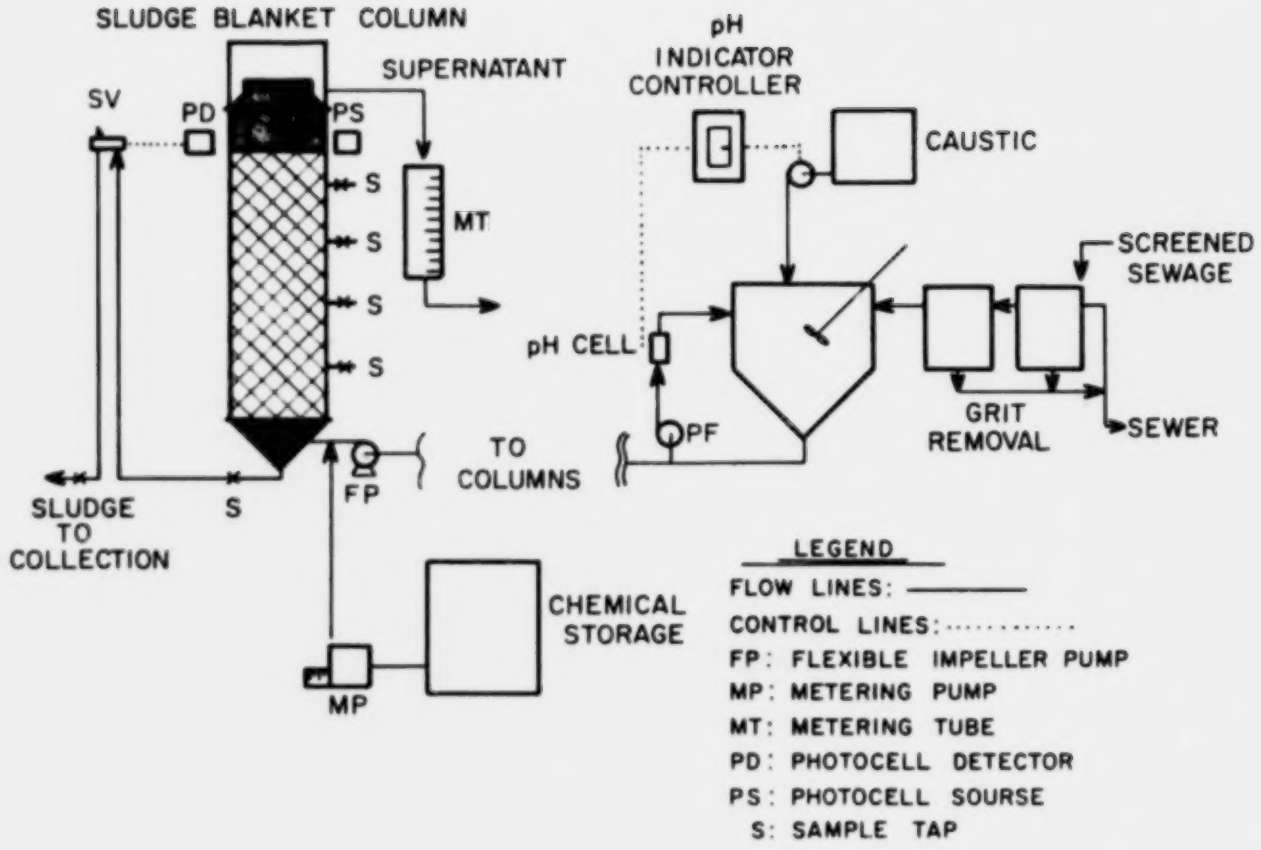
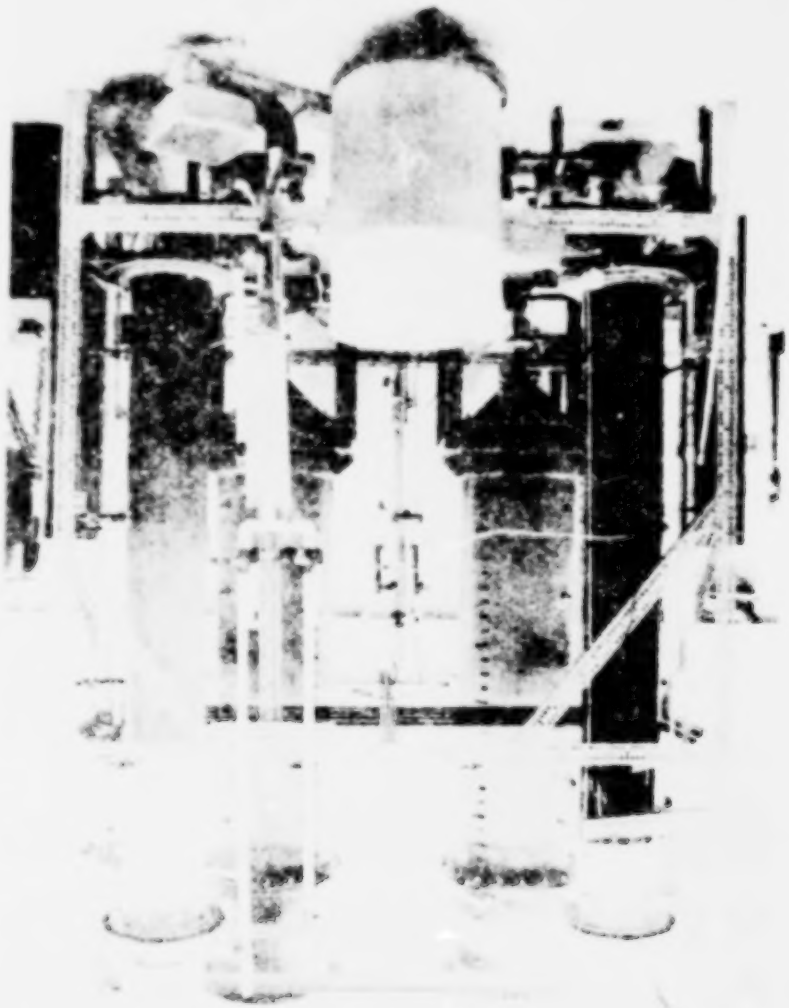


FIG 3 SYSTEM FLOW DIAGRAM



SECTION V

EXPERIMENTAL PROCEDURE

Wastewater Variation and Sampling

The experimental design plan required that for each experiment the independent variables be fixed at prescribed values. Owing to the uncontrolled variation in wastewater composition, corresponding variation in the system response was always present, and over the period of a day's operation, the response to the controlled variables would tend to be obscured by wastewater variation. It was concluded, therefore, that composite sampling was not indicated and that repeated sampling during a daily period of minimum wastewater composition variation should be followed.

An independent study of the Chapel Hill treatment plant influent by the UNC Wastewater Research Center (11) showed that there were two periods during an average day when the quantity and composition of the influent varied the least. These occurred between 0400 and 0800 hours at the low daily level and again between 1200 and 1600 hours at the high daily level. Accordingly, most experiments were scheduled for sampling during these times. This, of course, had the effect of providing data having the largest possible variation in wastewater composition, but the effect of this variation could be examined during the statistical treatment of the data.

Each experiment was assigned to be conducted at either the steady-state high feed concentration period or the steady-state low feed concentration period, the assignment being based upon a randomization of the order of execution. This was necessary to avoid confounding the desired measurements of performance with changes in feed concentration.

Procedure

Owing to the rapid formation of the sludge blanket under most conditions, an apparent steady state was usually reached within 4 to 6 hours after start-up. Occasionally during rainy weather an adequate floc could not be achieved at a low chemical dose (150 mg/l) or a high controlled pH (about 9). The usual practice was to begin operation early on Monday and to take samples on Tuesday, then changing operating variables and sampling again on Thursday. During periods of high experimental activity, the 24-inch diameter columns were allowed to operate throughout the weekend, since their larger volume required more time to fill during start-up.

Preceding the expected test period, samples of effluent were measured for turbidity using a Hach Model 2100 turbidimeter. When the turbidity of 4 to 6 effluent samples taken over an hour appeared to be constant, an initial set of all stream samples was taken. Effluent turbidity was monitored during the next hour, and if no serious changes occurred, a second set of samples was taken.

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A further criterion for steady operation was the continued control of the blanket level by regular automatic sludge discharge. Occasionally, from unknown causes, the blanket stopped accumulating sludge to cause the interface to recede or at least to remain below the desired level for an extended period. During this time the sludge would thicken to give an atypical sample. When this occurred, the test run had to be stopped, since the resulting samples gave inconsistent material balances. Usually two sets of samples were taken one hour apart, but several runs were made with a third set after the second hour of operation. The analyses of these samples were averaged when making calculations.

Sample Analyses

All samples were analyzed for the following:

Total organic carbon (TOC), mg/l
Total suspended solids (SS), mg/l
Soluble phosphorus (as P), mg/l
Total phosphorus (as P), mg/l
Coagulant metal ion (Al^{+++} or Fe^{+++}), mg/l.

Five-day BOD analyses were obtained only on the second sample of effluent and sewage streams to keep the load on the lab to a manageable level.

Individual TOC analyses were repeated at least twice to minimize error.

Suspended solids were determined for influent and effluent samples by filtration through glass fiber filters. For the determination of suspended solids in sludge, the fiber mat procedure is not practical. Sludge samples were centrifuged at 7000 g to separate the solids which were then dried and weighed. The residual solids in the centrifugate were determined by filtration on fiber mat filters and the weight of both solids combined to give the result for the entire sample.

Total phosphorus was determined by the automated stannous chloride method (15) following digestion of the entire sample by persulfate digestion. Dissolved phosphorus was determined by the same procedure following filtration through a membrane filter. Coagulant metals (Al^{+++} and Fe^{+++}) were analyzed by atomic absorption spectroscopy. Although the ferric oxidation state is indicated, the analysis represents the total iron present in the sample.

All determinations except phosphorus and metals were made within 24 hours of sampling and usually the same day. Phosphorus and metal analyses were run on scheduled days. The phosphorus samples were preserved by adding mercuric chloride and refrigerating; metals samples were acidified by adding hydrochloric acid.

Sewage Analyses

Table 1 lists the mean and extreme values for the measured constituents in raw, degritted wastewater used as influent to the process.

TABLE 1

Analysis of Raw, Degritted Wastewater Influent

	Max. Value mg/l	Min. Value mg/l	Mean Value mg/l
Suspended Solids	328	50	176
Total Organic Carbon	235	31	130
Soluble Phosphorus (as P)	10.7	1.6	6.4
Total Phosphorus (as P)	16.3	2.9	9.2
Al^{+++}	10	0.05	0.9
Fe^{+++}	2	1.0	1.4
BOD_5	224	42	145
Alkalinity, mg/l $CaCO_3$	166	100	140

Sludge Settling Measurements

It was initially proposed to apply a nuclear absorption technique to the measurement of sludge density variations and to determine sludge settling rates by this method. When sludge samples became available, however, it was found that the difference in density between the sludge and solids-free water was too small to give acceptable accuracy with a nuclear measurement. Consequently, this method was not attempted, and sludge settling rates were determined by direct visual measurement of the sludge interface position with time.

A detailed description of the sludge settling rate experiments is given in Section IX of this report.

SECTION VI

EXPERIMENTAL DESIGN

Plans for experiments were directed toward three goals: to assess the significance of process variables, to determine the effective ranges of these variables, and to model the performance of the clarifier. Five process variables were studied: the column diameter and four operational variables--upflow velocity, coagulant dose, blanket depth, and pH. The significance of these variables was judged statistically by measuring the effects of changes in their levels and comparing the measured effect with its experimental error. In addition, the significance of interactions of the variables was assessed. Effects assessed included effluent concentrations of suspended solids, total organic carbon, phosphorus and aluminum, and the volume of sludge produced.

The effective ranges of the operating variables were determined as the "factor space" within which the clarifier could be operated. Column diameters of 1 foot and 2 feet were compared, primarily to determine how readily the smaller diameter system could be scaled up. No attempt was made, however, to identify or measure all the elements of scale-up.

The performance of the clarifier was modeled by means of modified second degree equations, each with an effluent quality parameter (e.g., concentration of phosphorus) as a dependent variable, and four operating factors as independent variables. Modifications of the second degree equations consisted of extra terms added to account for the effects of the column diameter, the level of the dependent variable in the raw sewage and any significant higher order interactions of the operating variables. The performance models were fitted to the data by the method of least squares.

The clarifier received wastewater at flow rates which could be controlled. The concentrations of pollutants contained in the raw wastewater could not be controlled, however. Suspended solids, TOC, phosphorus, and aluminum in the wastewater were measured; and the measurements were averaged for each experiment.

In contrast to the uncontrolled variation of the wastewater quality, the operating variables were set and held at prescribed levels. An experiment consisted of adjusting the pH of the influent to a prescribed value, adding the prescribed coagulant, and passing it through the column at a prescribed upflow velocity. The depth of the sludge blanket was controlled independently.

Experiments with Alum as the Coagulant

A 2^4 factorial experimental design was employed to study the four operating variables in each size column. This design inherently met the data requirements for statistical tests to be applied. It spread the experiments systematically throughout the factor space so that the

limits of good operation could be defined. It could be expanded in a number of ways to generate data for a second degree model.

The levels of each of the five process variables which were prescribed for the factorial design were as follows: column diameters of 1 foot and 2 feet; upflow velocities of 9 and 12 feet per hour; coagulant doses of 150 and 250 ppm; blanket depths of 3 and 7 feet; and pH values of 8 and 9.

Upon application of the design, the clarifier failed to function at some of the prescribed operating conditions at a pH of 9, thus indicating that this pH was an upper bound for operation of the system. The experimental design was therefore expanded away from this limit by prescribing experiments at a pH of 7. The previous lower limit for pH was 8.

Additional levels of four of the variables were run to provide data for fitting the performance model as follows: upflow velocities of 6 and 15 feet per hour; coagulant doses of 200 and 300 mg/l; and a blanket depth of 5 feet. These additional runs were made at a pH of 8, since experience showed that this value always resulted in satisfactory operation. Since the data obtained at pH 9 could be used, a fourth level of pH was not necessary.

Experimental error was measured by repeating 13 of the experiments once and 3 of them twice. The data from a total of 51 experiments were analyzed.

Analysis

The data were analyzed statistically using regression analysis (3) techniques to determine the statistical significance of the effects and interactions, and to assess the goodness of fit of selected models.

Several models were fitted to the data. The best model, in terms of accounting for the greatest percent of the total variance in the measures of performance, contained a term for the effects of the raw wastewater, all main effects of operating variables and column diameter, all two-factor interactions, four quadratic terms and the following higher order interactions: diameter × alum dose × blanket depth; velocity × blanket depth × pH; diameter × velocity × alum dose × blanket depth × pH.

Experiments with Ferric Chloride as the Coagulant

Only three operating variables were studied: upflow velocity, coagulant dose and pH. The eight experiments carried out with ferric chloride as coagulant divide into two sets of four. Each set is a two-level factorial design to study velocity and pH at a constant level of ferric chloride. The sets employed different levels of ferric chloride dose. Also, one set employed upflow velocities of 12 and 15; the other, 9 and 12 feet per hour. The data obtained do not provide a self-contained measure of experimental error which was available for the alum experiments.

Therefore, experimental errors were assumed to be approximately the same as those measured in the analysis of the experiments with alum. The two sets of four experiments were combined to fit a regression model having linear terms for velocity, ferric chloride dose, pH and influent concentration of the contaminant and a quadratic velocity term.

SECTION VII

RESULTS AND DISCUSSION OF EXPERIMENTS USING ALUM

The original design was followed using pH levels of 8 and 9 until poor operation at pH 9 forced the design to be altered by substituting pH 7 runs. Actually, nine runs were made at pH 9 before reverting to the alternate design. Thus, the prescribed two-level design was completed using pH 7 and 8 with the runs at 9 considered supplementary. Thirteen of the 53 runs were replicates, and three experiments were repeated twice to establish a statistic for error. Included in the 53 runs are six test runs made at an interim point of the design.

Examination of the results disclosed that two experiments were so different from the remainder that they could be legitimately discarded; poor samples were believed responsible. A total of 51 test runs were finally used in the correlations. The data from these runs are displayed in Appendix A.

During the experimental phases of the study, it was noted that influent Al^{+++} concentrations determined by analyses of the influent samples frequently were different from the intended value prescribed by the experimental design. Actual measured values were used in the regression analyses.

Data Correlation

The test run data were analyzed using a standard multiple regression procedure programmed in A Programming Language (APL) for the IBM 360/75 computer (9). The original data were stored in program work spaces for easy access to any alternate regression model desired. Several models were tried, and the one producing the smallest residual variance was selected as the best. The same regression model was found best for all the variables studied except inorganic phosphorus, which required a slightly different equation to achieve the best fit.

The first regression model is:

$$Y_j = b_{oj} + c_{oj}X_{oj} + \sum_{i=1}^{5} a_{ij}X_i + \sum_{\substack{i,k=1 \\ i \neq k}}^{5} a_{ijk}X_iX_k + \sum_{i=2}^{5} c_{ij}X_i^2 + d_{1j}X_1X_3X_4 + d_{2j}X_2X_4X_5 + d_{3j}X_1X_2X_3X_4X_5 \quad (7\text{-}1)$$

This model was used to correlate the effluent concentrations of suspended solids, TOC, total phosphorus, residual Al^{+++} and the volume percent sludge produced, which are represented by Y_j.

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The model fitting the concentration of soluble phosphorus in the effluent best was found to be:

$$Y_j = b_{oj} + c_{oj}X_{oj} + \sum_{i=1}^{5} a_{ij}X_i + \sum_{\substack{i,k=1 \\ i\neq k}}^{5} a_{ijk}X_iX_j + \sum_{i=2}^{5} c_{ij}X_i^2$$

$$+ d_{1j}X_2X_5^2 + d_{2j}X_3X_5^2 + d_{3j}X_4X_5^2 \ . \qquad (7\text{-}2)$$

In both of these models the following notation represents the five independent variables studied:

X_{oj} = influent concentration of contaminant j

X_1 = column diameter, D, inches

X_2 = upflow velocity, U, ft/hr

X_3 = alum dose, Al, mg/l

X_4 = blanket depth, L, ft

X_5 = adjusted pH of the wastewater before coagulant addition.

The effects and interactions of the process variables were estimated in the form of parameters of the mathematical model. Each parameter so estimated was tested statistically to determine the probability of obtaining the experimental value if the parameter had a true value of zero. The t-test was employed. For the experiments with alum, whenever the probability of a true value of zero was found to be less than 0.05, the parameter was judged to have a real effect. The numerical values for the coefficients are listed in Appendix B. Because these are empirical formulas, they should not be expected to be accurate outside the range of the data.

It is not practical to use the correlations for a hand calculation to predict a result, owing to the fact that a large number of significant figures must be retained to avoid round-off error. The computer has prepared a set of graphs from the correlations which should be adequate for most purposes, however, and provides a visual representation of the effects of the variables on sludge blanket performance.

The statistical analysis showed that diameter effects were not significant except for the case of sludge production; even in this case, the diameter effect was second order, as it appeared as an interaction factor with alum dose and blanket depth but not as a main effect.

No practical purpose is served by presenting the graphical results showing effects of non-significant variables. Excepting the correlation for suspended solids in the effluent, the graphs prepared from the correlations present the effects of the significant variables including predicted maximum and minimum values. These are not confidence limits, but are the extreme values resulting from the contributions of the non-significant variables. Thus the charts present a range of results which might be expected with the particular significant variables chosen for any value of the remaining non-significant variable within the experimental range.

The above procedure has not been followed for presenting the suspended solids correlation because it was desirable to draw attention to several qualitative effects which were of interest despite their lack of statistical significance.

If one wishes to reproduce the curves from equations (7-1) and 7-2), the value of $X_1 = 24$ should be used. Other values of X_1 will give slightly different results but not statistically different from those shown on the curves. Values for any of the variables not within the ranges studied should be used with caution, as large extrapolations are not warranted.

Individual data points will generally not agree precisely with the curves owing to experimental error and operating conditions different from those chosen in making the plots. In assessing the goodness of fit, the standard deviation between observed and correlation values should be noted along with the percent variance removed. These are listed with each correlation in Table 3.

In four of the six correlations, the corresponding value for the quantity in the influent to the sludge blanket had a significant effect on the same quantity in the effluent. The graphs were prepared using the average of the influent; thus a correction term is given in the text and should be applied whenever the influent has a composition different from the base value.

Suspended Solids in Effluent

Figures 6A and 6B show the graphical representation of the correlation between the suspended solids concentration in the effluent and the variables. From the regression analysis the terms in the regression equation having significant contributions to the correlation in comparison to their error of estimation are:

$$X_5 = \text{pH}$$

$$X_3^2 = \text{Al} \times \text{Al}$$

$$X_5^2 = \text{pH} \times \text{pH}.$$

Because of the quadratic terms the correlations show that the suspended

DIAMETER 24"
UPFLOW VELOCITY 9FT/HR

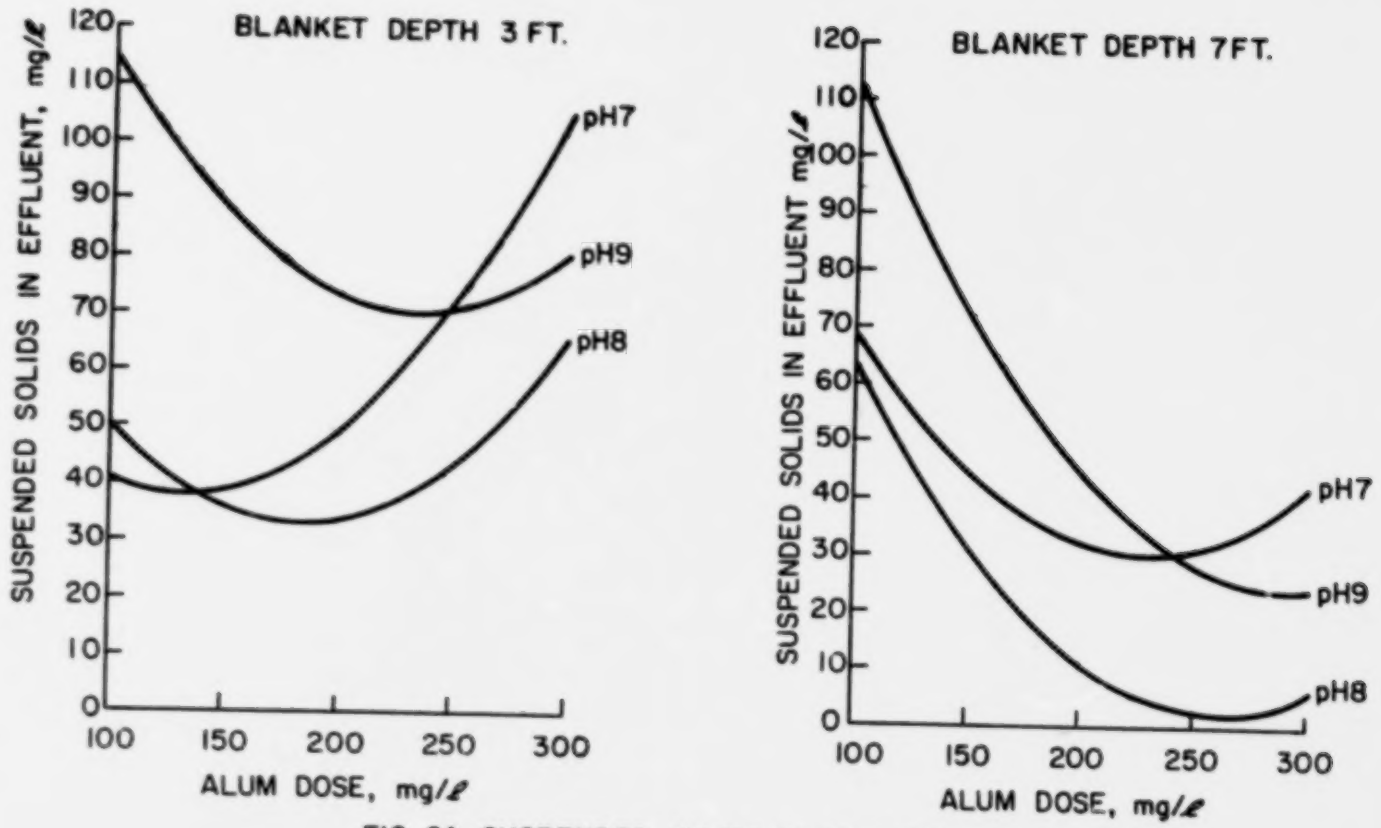

FIG. 6A SUSPENDED SOLIDS IN EFFLUENT

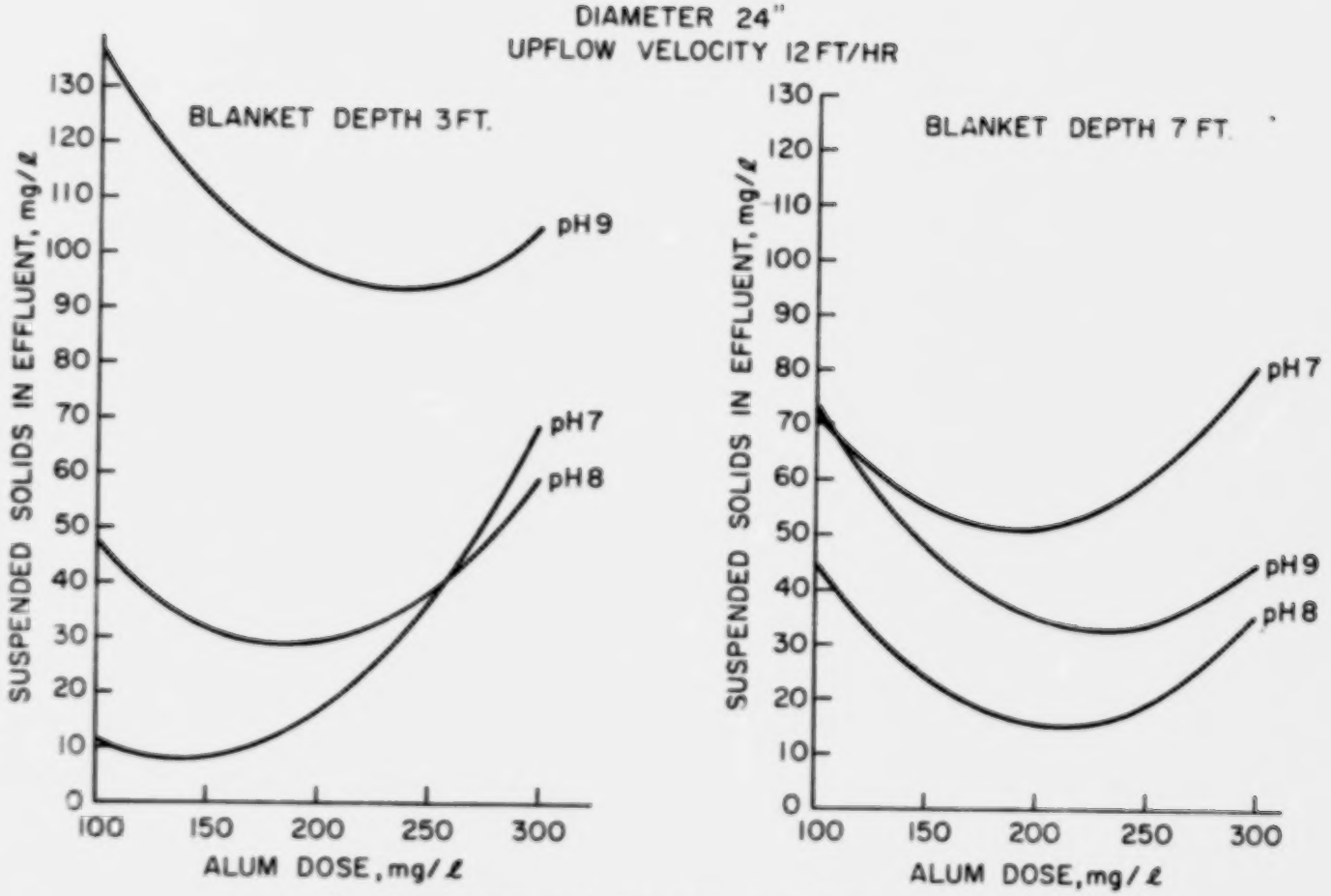

FIG. 68 SUSPENDED SOLIDS IN EFFLUENT

solids in the effluent are the smallest for different values of pH. The alum dose at the minimum shifts to higher values as the pH increases from 7 to 9. With the exception of the curves for U = 9 ft/hr and L = 3 ft, pH 8 is seen to produce the smallest effluent suspended solids at an alum dose between about 200 and 275 mg/l. The curves for both pH 7 and pH 9 give higher effluent suspended solids.

Although the contributions of blanket depth and upflow velocity were statistically non-significant, it is seen that the correlations predict qualitatively that the deeper blanket results in a smaller effluent suspended solids, at least for U = 9 ft/hr. The results for the 3 foot blanket are less reliable because of the difficulty in achieving a stable interface, particularly at the higher velocities.

For the 7 foot blanket, the qualitative indication is that the lower velocity produces less suspended solids.

Discussion

A significant effect of both alum dose and pH on the suspended solids removal corresponds to observations made by Miller and West (16) although their work was done on river water and not sewage. They noted minima in the data for effluent turbidity versus alum dose which seemed to have little relationship to blanket depths in the range of 5 to 9 feet.

Miller and West also concluded that an optimal pH for turbidity removal occurred between 6.5 and 7.0 as measured in the flocculating mixture. This agrees generally with the present finding that pH 8 gave a lower effluent solids than either pH 7 or pH 9. The pH variable of the present experiments was measured before the alum addition, and thus the pH value for the flocculating mixture was lowered by the alum. The average pH of the influent after alum addition as measured during the test runs is shown in Table 2.

TABLE 2

Average pH After Alum Addition

Initial pH	Alum Dose, mg/l	
	150	250
7	6.1	5.4
8	6.4	5.6
9	6.8	6.7

These final pH values may explain a shift in the minima of the curves in Figures 6A and 6B to higher alum dose values as the initial pH is increased from 7 to 9, i.e., the minima probably correspond to the optimum flocculation pH values.

Miller and West also noted the effects of blanket depth and upflow velocity on effluent turbidity. Generally, deeper blankets produced less turbidity, although the data are scattered. Increasing upflow velocity produced greater turbidity in the effluent. Both these observations correspond to the qualitative predictions of the present correlations and are in agreement with the physical point of view that a deeper blanket provides more opportunity for small particle capture and agglomeration and lower upflow velocities reduce the tendency for particle elutriation from the blanket interface.

Although the variables--blanket depth, L; upflow velocity, U; and column diameter, D--were not found to be statistically significant within the limited ranges tested, the combined contribution of these variables and interactions needs to be included to account for the variation remaining after the major contributions of pH and Al have been removed. The correlation accounted for 78.1 percent of the total variation, and the regression equation fitted the data with a standard deviation of 4.4 mg/l.

A minor effect due to suspended solids in the influent was found. Since the curves in Figures 6A and 6B were computed for a mean influent suspended solids concentration of 176.3 mg/l, a correction to the predicted effluent suspended solids should be made if the influent suspended solids differs from this value. This correction is $0.068(C_s - 176.3)$mg/l, where C_s is the influent suspended solids, mg/l, and should be added to the effluent suspended solids given by the curves in Figures 6A and 6B.

Total Organic Carbon in the Effluent

Figure 7 shows the graphical results of the correlation for TOC. The regression analysis showed the significant term in the regression equation to be

$$X_2X_5 = U \cdot pH.$$

The remaining variables were not found to contribute significantly to the regression. The major difference between the predicted results at U = 9 and U = 12 is seen to be a widening of the limits within which the effluent TOC may be expected to fall at the given pH. The curves for U = 9 indicate possibly better TOC removal at values of pH between 7.5 and 8.0, while the curves for U = 12 show generally poorer treatment with increasing pH. Generally, effluent TOC was unaffected by the variables except at higher velocity and higher pH.

The correlation accounted for 75.8 percent of the total variation and

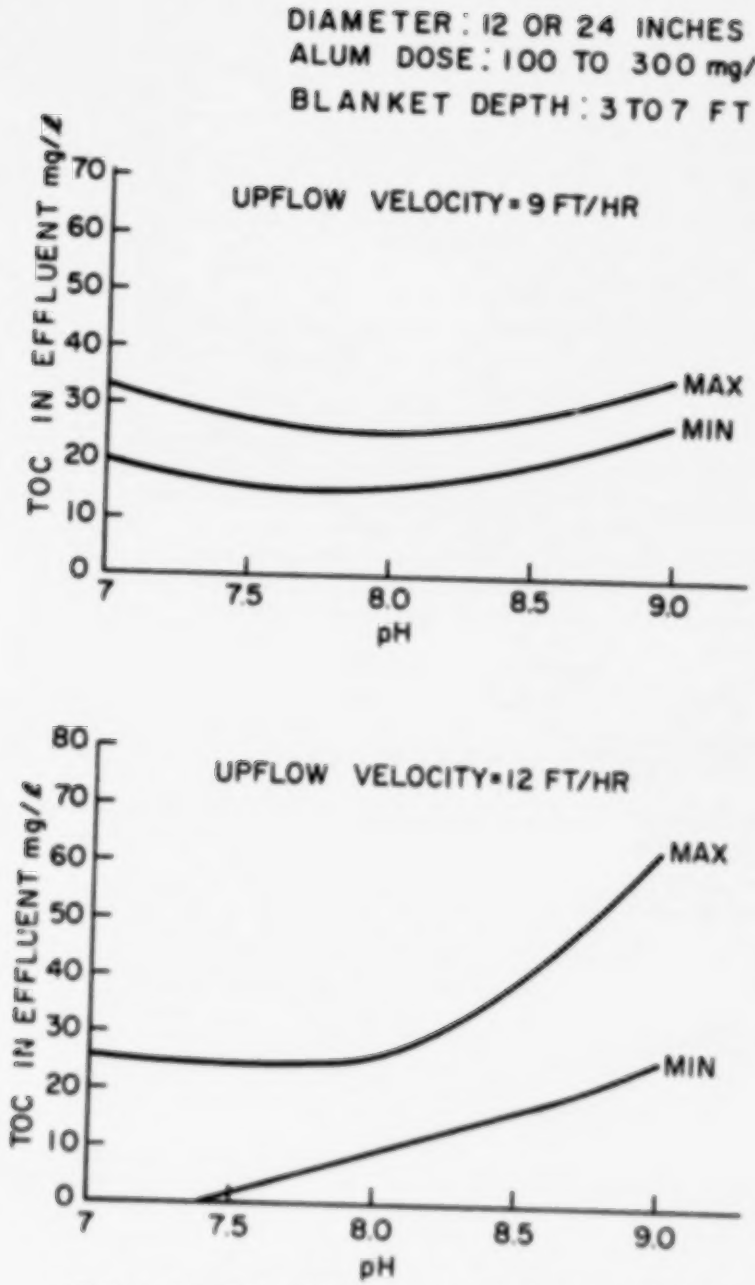

FIG. 7 TOTAL ORGANIC CARBON IN EFFLUENT

gave a standard deviation of 3.5 mg/l TOC in the effluent. A small correction of $+0.075(C_c - 130.1)$mg/l TOC in the effluent may be made for influent TOC concentrations (C_c) different from 130.1 mg/l.

Soluble Phosphorus in the Effluent

Figures 8A and 8B show the graphical representation of the correlation for soluble phosphorus, in mg/l as P, in the effluent. The regression analysis showed the significant terms in the regression equation to be

$$X_3 = Al$$

$$X_3X_5 = Al \times pH$$

$$X_3^2 = Al \times Al$$

$$X_3X_5^2 = Al \times pH \times pH.$$

The remaining variables were not found to contribute significantly to the regression.

The curves represent the maximum and minimum values at the given conditions of alum dose and pH predicted over the experimental range of the insignificant variables. It can be seen that the effluent soluble phosphorus generally decreases with increasing alum dose, except for influent pH 8 which indicates a minimum between 200 and 250 mg/l alum. Soluble phosphorus removal appears to be best at pH 8, worst at pH 9, with considerable overlapping for alum dose 200 and 300 mg/l.

The correlation predicted negative values for some values of alum dose and pH because of its inability to distinguish low values of effluent phosphorus from the regression error. The correlation accounted for 76.9 percent of the variation and gave a standard deviation of 0.94 mg/l. From the value for the standard deviation, one concludes that no real difference exists between points predicted to be less than 1 mg/l.

An effect due to the concentration of soluble phosphorus in the influent was found. If influent soluble phosphorus, C_p, is different from 6.375 mg/l, a correction of $+0.369(C_p - 6.375)$mg/l should be made to the effluent soluble phosphorus.

A discussion of phosphorus removal from wastewaters is presented in a following section.

Total Phosphorus in the Effluent

Figures 9A and 9B show the graphical results of the correlation for total phosphorus in mg/l as P. The significant terms of the regression equation were found to be

$$X_5 = pH$$

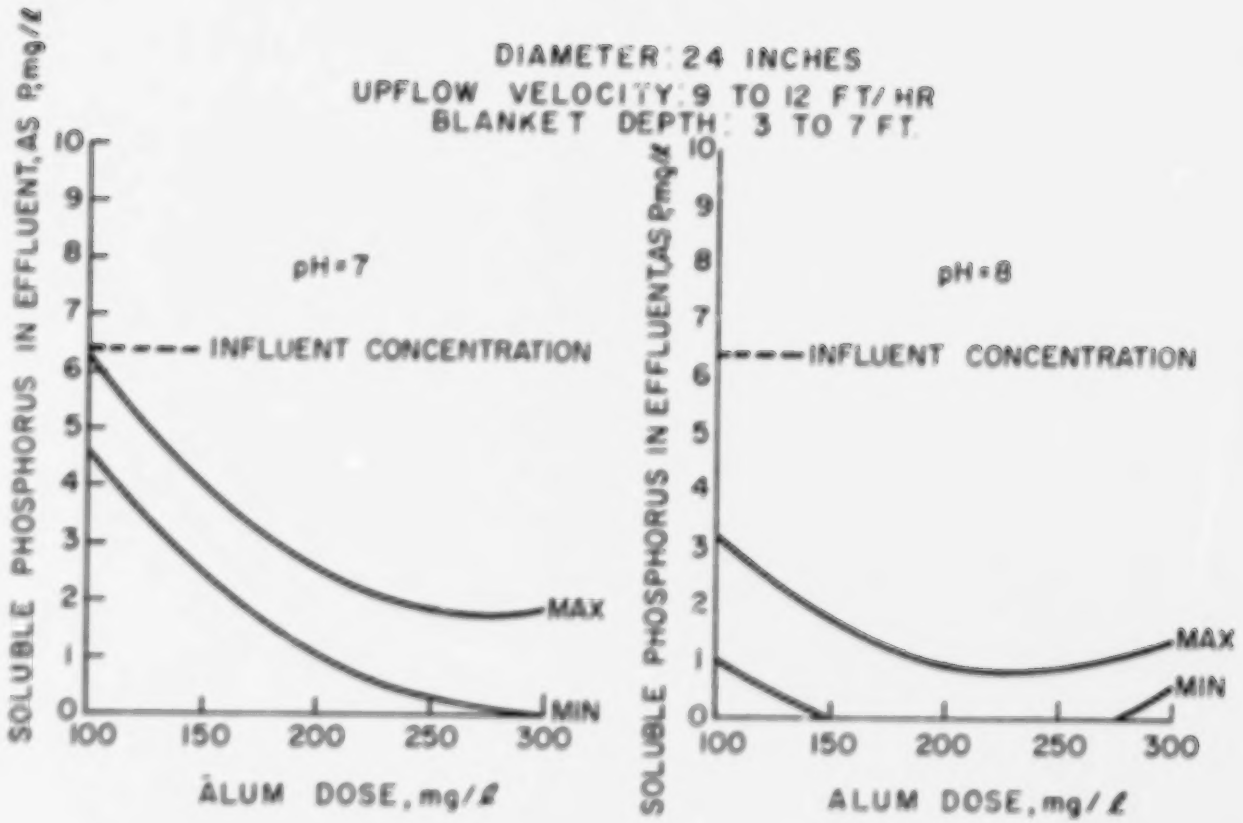

FIG. 8A SOLUBLE PHOSPHORUS IN EFFLUENT

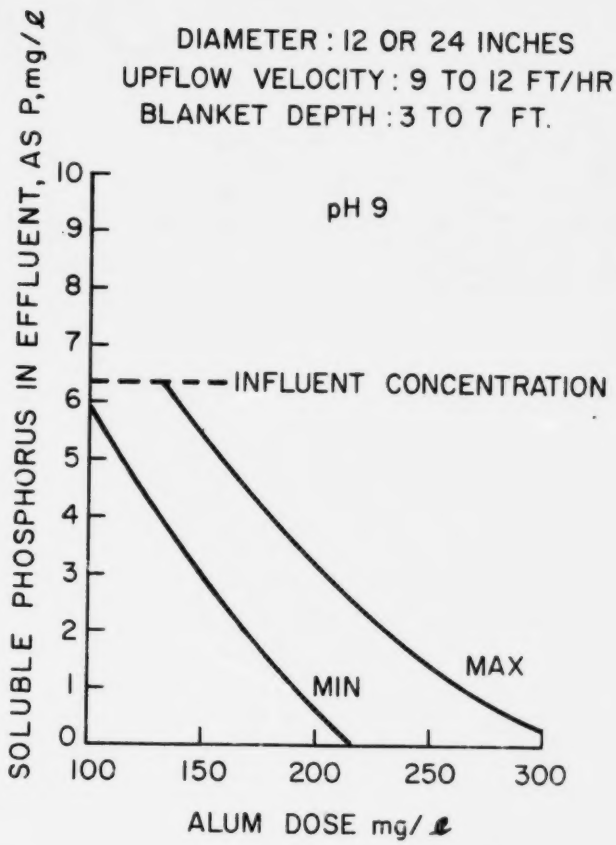

FIG. 8B SOLUBLE PHOSPHORUS IN EFFLUENT

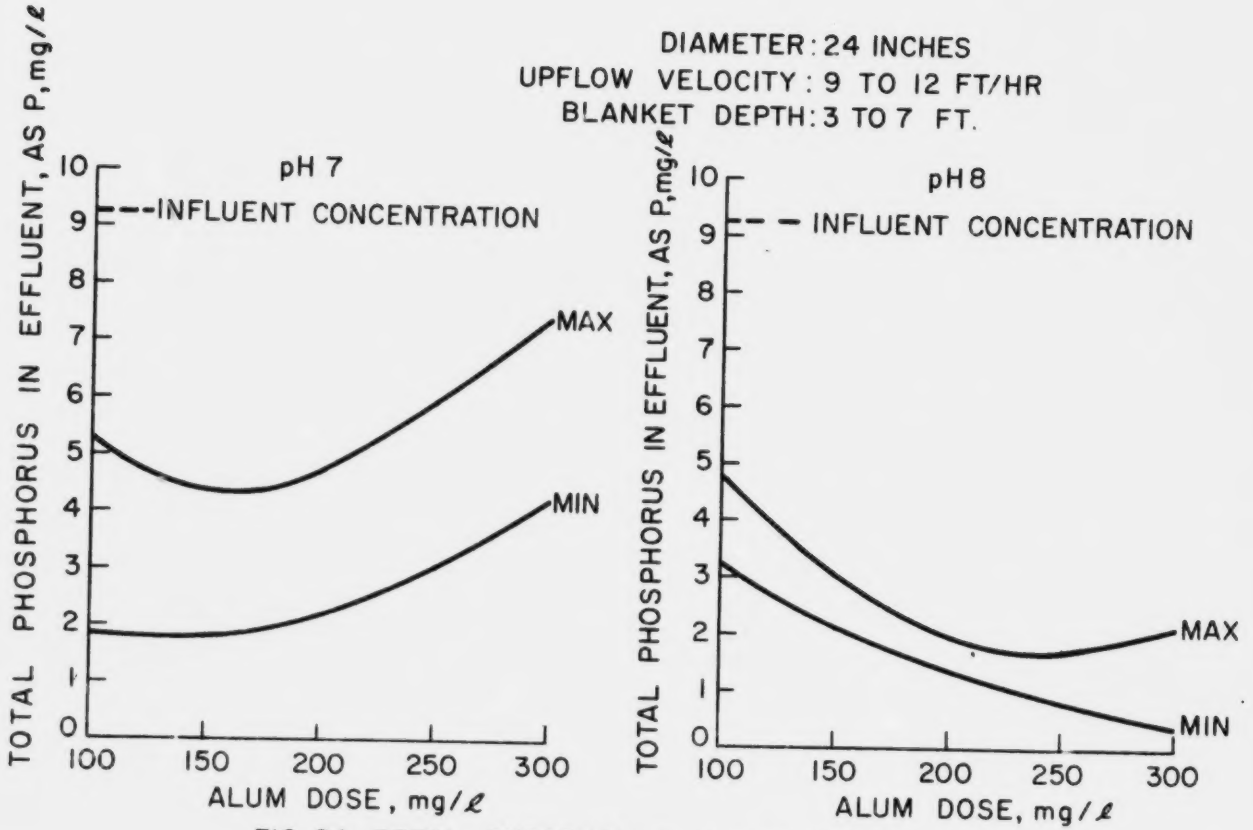

FIG. 9A TOTAL PHOSPHORUS IN EFFLUENT

DIAMETER : 12 OR 24 INCHES
UPFLOW VELOCITY : 9 TO 12 FT/HR
BLANKET DEPTH : 3 TO 7 FT.

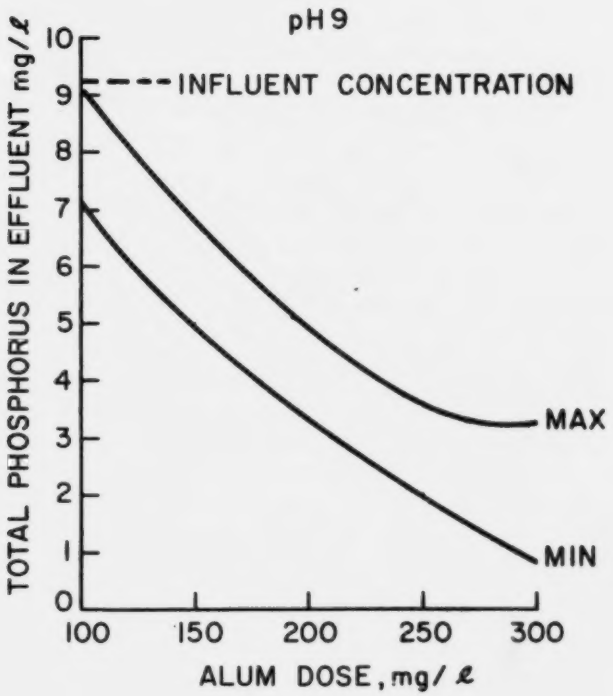

FIG. 9 B TOTAL PHOSPHORUS IN EFFLUENT

$$X_3X_5 = Al \times pH$$

$$X_5X_5 = pH \times pH.$$

The remaining variables were not found to contribute significantly to the regression.

It can be seen that increasing alum dose results in lower effluent total phosphorus except at pH 7 and that the lowest values occur at an influent pH of 8.

The correlation accounted for 74.5 percent of the variation and gave a standard deviation of 1.2 mg/l. An effect due to the concentration of total phosphorus in the influent was found. If influent total phosphorus, C_p, is different from 9.246 mg/l as P, a correction of $+0.368(C_p - 9.246)$ mg/l should be made to the effluent total phosphorus concentration.

A discussion of phosphorus removal from wastewater is presented in the following section.

Discussion of Phosphorus Removal

The correlations for the concentration of soluble and total phosphorus in the effluent showed that the significant variables were alum dose and pH, as well as the concentration of phosphorus in the influent. The effects of these same variables on phosphorus removal have been noted by other investigators.

In a study using secondary effluent from the same plant, Malhotra *et al* (13) studied the removal of phosphorus from samples with and without pH adjustment. They found that the percent removal increased with alum dose between 100 and 250 mg/l but that significantly better removals were achieved when the initial pH of the effluent was adjusted from 8.0 to 6.0. Further experiments led them to conclude that the optimum pH zone for removal of phosphorus with alum was 5.50 to 6.0. They found considerable variation in percent removed at the same alum dose and pH which was attributed partly to initial phosphorus concentration and partly to "unknown components" in the sewage. For example, at pH 8.0 and 200 mg/l alum they observed a range of removals between 81 and 76 percent for initial concentrations of total phosphorus of 7.86 and 10.05 mg/l as P, respectively. The residual concentrations would have been about 1.5 and 2.4 mg/l, respectively. Comparing this with the correlations in Figure 9A, at 200 mg/l and pH 8 the range of residual total phosphorus is seen to be from 1.4 to 2.0 mg/l, which is in reasonable agreement with Malhotra's data. At pH 8 and 100 mg/l, the residual phosphorus from Malhotra's data is between about 4.6 and 5.5 mg/l, while Figure 9A shows the expected range of 3.2 to 4.8 mg/l, again in reasonable agreement. Comparing the correlations at pH 7 and pH 9 with Malhotra's data, however, does not give as good agreement, since higher effluent phosphorus concentrations are predicted. The range at pH 7 from Malhotra's data is about 0.6 to 1.9 at 200 mg/l as compared with 2.2 to 4.8. The range found by Malhotra for pH 9 and 200 mg/l is from

2.2 to 2.8 while the correlations predict a range from 3.3 to 4.9. Although there are differences between the effects of pH noted in this work and that of Malhotra, it is not unreasonable to expect different results stemming from widely different wastewater characteristics.

When considering phosphorus removal by Al^{+++} and Fe^{+++}, it is useful to distinguish between reaction and removal. The reactions of phosphorus with Al^{+++} and Fe^{+++} depend upon the forms of phosphorus present and the other substances in the water which can also react with these metal ions (e.g., OH^-, colloids). The removal of phosphorus depends upon physical and chemical properties of the solid materials which are formed.

Most of the phosphorus in secondary effluent is orthophosphate (1). The majority of the investigations of P removal by iron^{+++} and aluminum^{+++} have dealt with synthetic wastes containing orthophosphate or with secondary effluent. In contrast, much less (on the order of 40 percent) of the phosphorus in raw domestic sewage is present as orthophosphate; the balance is comprised of polyphosphates and particulate phosphorus (10).

Thermodynamic calculations describing the effects of pH on the precipitation of orthophosphate as $FePO_4(s)$ and $AlPO_4(s)$ have been made by several authors (19). Experiments are in reasonable agreement with these predictions (8). $AlPO_4(s)$ has a minimum solubility at about pH 6.0, while $FePO_4$ is least soluble at about pH 5.0. The optimum pH increases slightly with increasing metal/phosphorus (Me/P) ratios. Excess metal ions (Me/P>1) are added because (a) Fe^{+++} and Al^{+++} also react with OH^-, and (b) other materials in secondary effluent (e.g., some soluble organics, bio- and other colloids) will react with these metals. At pH levels above these values (pH 5 for $FePO_4$, pH 6 for $AlPO_4$), more of the iron^{+++} or aluminum^{+++} is used to react with OH^- ions, forming $Fe(OH)_3(s)$ and $Al(OH)_3(s)$. These solids have a positive charge below their isoelectric points and can adsorb appreciable quantities of orthophosphate. Alumina columns have been successfully tested as adsorbents for inorganic phosphorus (1). As a result, considerable removal of orthophosphate can be accomplished by Fe^{+++} at pH > 5.0 and by Al^{+++} at pH > 6.0 due to this adsorption. Me/P ratios significantly greater than 1 are used. For example, Me/P ratios of about 1.5 are often sufficient to achieve good precipitation of orthophosphate at the pH of minimum solubility, while Me/P ratios of 3 or higher are used when higher pH levels lead to the formation of the solid $Me(OH)_3$ and subsequent orthophosphate adsorption. (At 200 mg/l the aluminum/total phosphorus ratio was about 2.1 for the present study.)

Precipitation and/or adsorption of polyphosphates are also possible using Al^{+++} and Fe^{+++}. Relatively few studies have been made. Cohen et al (4) noted significant interference by tripolyphosphate in the coagulation of water using ferric sulfate. Tenney and Stumm (20) noted that soluble complexes were formed between Al^{+++} and pyrophosphate at $Al^{+++}/P < 1$; when the molar dosage of Al^{+++} exceeded the molar phosphorus concentration, precipitation resulted. Very little information is available on the coagulation of phosphorus-containing particulates in

wastewater by Al^{+++} and Fe^{+++}. It is probable the coagulation is effective at pH levels in the order of 7.0, somewhat higher than that for $MePO_4$ precipitation. In this case Me/P ratios could be less meaningful; coagulant dosage would depend more upon the concentration of colloids to be aggregated.

The precipitates formed by many of the preceding reactions can be colloidal. Stated another way, the optimum pH for phosphate precipitation does not necessarily equal the optimum pH for phosphate removal.

Given this wide variety of materials and reactions, what may happen when raw sewage is treated with Al^{+++} or Fe^{+++}? It seems likely that in the experiments conducted during this study, some Al^{+++} reacted with orthophosphate and polyphosphates to form a mixed hydroxophosphatoaluminum precipitate. It is not possible to evaluate when removal involved phosphate precipitation and when adsorption might have occurred without data describing the pH of the system after the addition of Al^{+++}. Some Al^{+++} may have reacted with soluble organics in the waste, although this is probably not significant. Additional Al^{+++} was used to coagulate sewage particulates, some of which contained phosphorus. Finally, some Al^{+++} may have been used to coagulate these various solid materials.

Residual Al^{+++} in the Effluent

Figures 10A and 10B show the graphical results of the correlation for residual Al^{+++} in mg/l. The significant terms in the regression equation were found to be

$$X_3 = Al$$

$$X_3X_5 = Al \times pH$$

$$X_2X_2 = U \times U.$$

The remaining variables were not found to contribute significantly to the regression.

At pH 7 residual Al^{+++} is seen to increase as the alum dose increases with considerable overlapping of the ranges indicated at the two upflow velocities of 9 and 12 ft/hr. For pH 8 and pH 9 there is still some overlapping for velocity at the lower alum dose, but the trends are more definite: Increasing the dose and lowering the velocity decrease the residual effluent Al^{+++}.

The correlation accounted for 70.9 percent of the variation and gave a standard deviation of 1.4 mg/l Al^{+++}. No significant effect of Al^{+++} concentration in the wastewater was found.

Discussion

The effect of pH on residual Al^{+++} can be explained qualitatively by

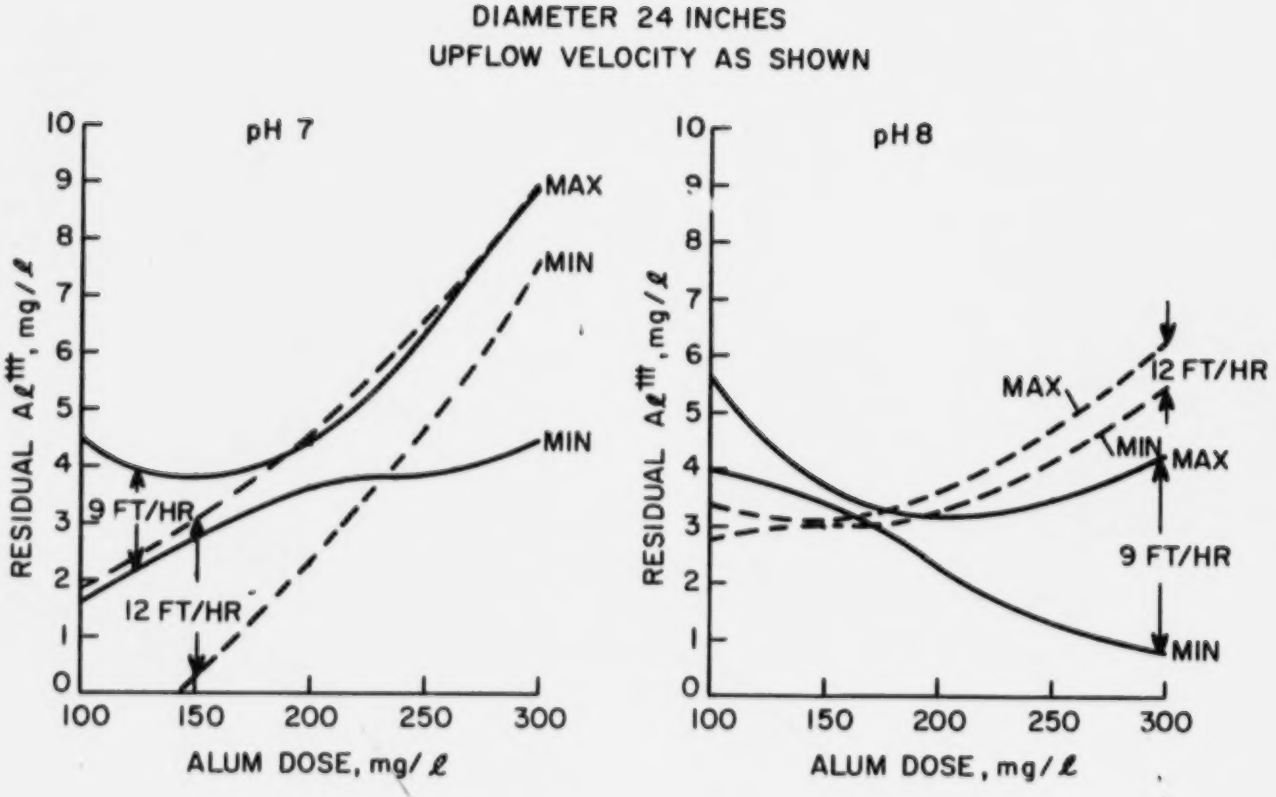

FIG. 10 A RESIDUAL ALUMINUM IN EFFUENT

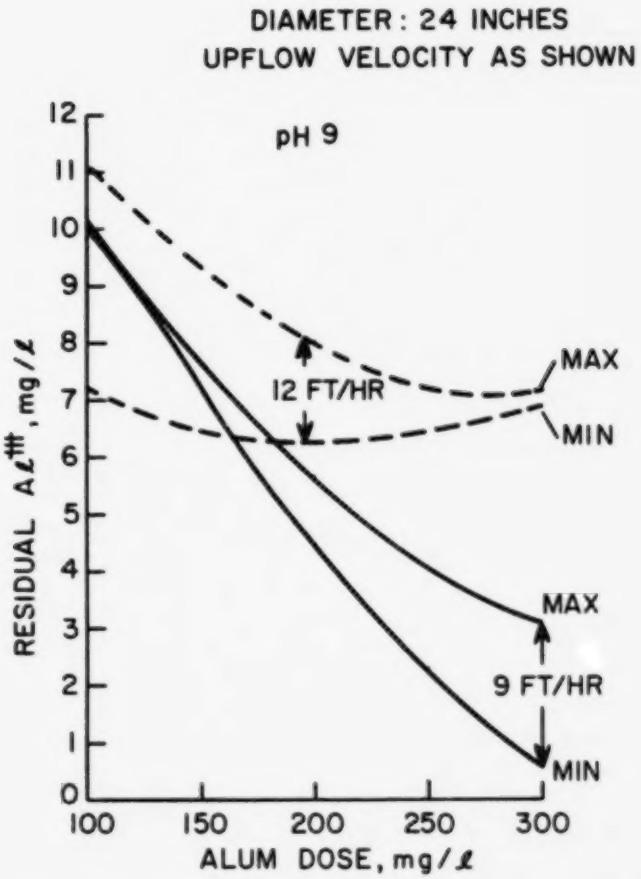

FIG. 10 B RESIDUAL ALUMINUM IN EFFLUENT

noting that the range of pH for minimum solubility of aluminum hydroxide is from about 5 to 7 (18) and that the final influent pH varied with the dose and the initial pH (cf. Table 2). Thus for the curves in Figure 10A for pH 7, the increasing dose probably depressed the final pH to values favoring dissolution of the aluminum and consequent higher residual values. The curves for pH 8 indicate that increasing alum dose may have caused the final pH to decrease from near the upper range of relative insolubility (pH 6.4 or greater) to a value near that for minimum solubility (pH 5.6). The final set of curves for pH 9 indicates the same effect, only the final resulting pH was higher (6.7 to 6.8) causing some solution of the aluminum.

The effect of upflow velocity on the residual aluminum can be explained for the pH 8 and pH 9 results by reasoning that once flocs have formed under the proper combination of pH and coagulant dose, the major cause of residual Al^{+++} would be from the elutriation of these flocs from the surface of the blanket. Thus a lower upflow velocity will result in less aluminum loss, which is borne out by the results. If, however, appreciable aluminum remains in solution, as for pH 7, the upflow velocity will not affect the loss. This is at least partially supported from the results shown in the plot for pH 7 where the velocity effects overlap considerably.

In their experiments coagulating river water, Miller and West (16) observed that increasing pH of the coagulating mixtures in the range 5.5 to 8.0 increased the aluminum in the effluent slightly. They observed that "contrary to expectations" the residual aluminum increased with dose and with upflow velocity, particularly at the higher upflow velocities (18 ft/hr), although the increase with dose was less at upflow velocities of 6 to 10 ft/hr. This agrees with the present result shown for 12 ft/hr. It should be noted that the alum dose in the Miller and West study did not exceed about 55 to 60 mg/l and their curves for the lower upflow velocity decrease in slope with increasing dose. The slope may well be reversed at higher doses.

Sludge Production

The significant terms in the regression equation were found to be

$$X_1X_3 = D \times Al$$

$$X_1X_4 = D \times L$$

$$X_3X_4 = Al \times L$$

$$X_1X_3X_4 = D \times Al \times L.$$

The remaining variables did not contribute significantly to the regression. The correlation is relatively poor in comparison with those for the other variables, accounting for 68.7 percent of the variance and

giving a standard deviation of 2.5 volume percent. This result indicates that other factors may have been responsible for the sludge production rate, e.g., the differences between 12- and 24-inch diameter column construction which could have influenced the thickening of the sludge below the inlet distributor.

The curves shown in Figure 11 are for the 24-inch diameter column only. Maximum and minimum curves for blanket depths of 3 and 7 feet are shown. Only results for pH 8 are shown, since the results for both pH 7 and pH 9 give negative values over parts of the dose range, a result of the poor correlation.

It is difficult to interpret the sludge curves with a high degree of confidence. It is seen generally that the deeper blanket produced less volume of sludge, which probably reflects the better flocculation achieved by a large number of particles. The sludge volume decreases with increasing dose for the 3 foot depth, but can increase with dose for the 7 foot depth.

BOD_5 Concentration in the Effluent

A regression between BOD_5 and TOC in the effluent was made with the following result:

$$BOD_5 = 2.10(TOC) - 12.1.$$

This correlation was found to account for 47 percent of the variance and gave a standard deviation of 3.5 mg/l BOD_5. While not as good a correlation as desired, the relationship is of value in predicting the effect of the operating variables on the BOD_5 via the TOC correlation.

Summary of Results of Experiments Using Alum

Table 3 summarizes the results of the statistical analysis and includes the statistics representing the goodness of fit of the regression equations and the statistically significant terms. The final column indicates whether or not the effect of influent on the effluent was significant.

Table 4 summarizes the treatment effects predicted at the best combination of operating variables within the ranges studied. Included in the table are maximum and minimum predicted values to indicate expected variation due to the total effect of non-significant variables. In some cases the predicted value coincides with one of the limits. The values of the operating variables chosen for the predictions are:

alum dose	:	250 mg/l
upflow velocity	:	9 ft/hr
blanket depth	:	7 ft
column diameter	:	24 in.
pH	:	8.

DIAMETER: 24"
UPFLOW VELOCITY: 9 TO 12 FT/HR
WASTEWATER pH: 8

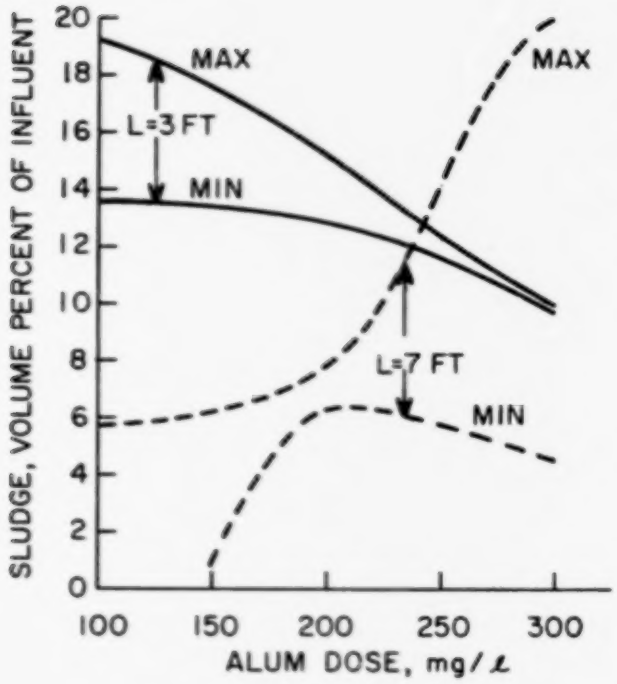

FIG. II SLUDGE PRODUCTION

TABLE 3

Summary of Regression Analysis of Experimental Data Using Alum

D = column diameter, in.; U = upflow velocity, ft/hr; Al = alum dose, mg/l;
L = blanket depth, ft; pH = pH

Dependent Variable	Percent Variance Removed	Standard Deviation	Significant Terms in Regression Formula	Influent Effect
Effluent Suspended Solids, mg/l	78.1	± 4.4 mg/l	pH Al × Al pH × pH	yes
Effluent TOC, mg/l	75.8	± 3.5 mg/l	U × pH	yes
Effluent Soluble Phosphorus, mg/l	76.9	± 0.94 mg/l	Al Al × pH Al × Al Al × pH × pH	yes
Effluent Total Phosphorus, mg/l	74.5	± 1.2 mg/l	pH Al × pH pH × pH	yes
Effluent Residual Al^{+++}, mg/l	70.9	± 1.4 mg/l	Al Al × pH U × U	no
Volume Percent Sludge	68.7	± 2.5 percent	D × Al D × L Al × L D × Al × L	no

TABLE 4

Summary of Predicted Treatment Effects Using Alum

(Numbers in parentheses are corresponding percent removals based on average influent concentration)

Contaminant	Average Influent Concentration mg/l	Maximum Predicted Effluent Concentration mg/l		Predicted Effluent Concentration mg/l		Minimum Predicted Effluent Concentration mg/l	
Suspended Solids	176.3	31	(83)	2.4	(98)	2.4	(98)
Total Organic Carbon	130.1	25.5	(80)	22.7	(83)	15.9	(88)
Soluble Phosphorus (as P)	6.4	0.9	(86)	0.8	(88)	0	(100)
Total Phosphorus (as P)	9.3	1.8	(81)	0.9	(90)	0.8	(92)
BOD_5	145	41.4	(71)	35.5	(75)	21.3	(85)
Residual Al^{+++}	0.95	3.5		1.3		1.3	
Sludge Production, volume % of influent		14.1		14.1		5.8	

The predicted effects of different values of the variables within the ranges studied may be found from the preceding graphs or by using the regression formulas. Extrapolations are not warranted, however.

SECTION VIII

RESULTS AND DISCUSSION OF EXPERIMENTS USING FERRIC CHLORIDE

Limited data were obtained using ferric chloride as a coagulant, the intent of the experiments being to provide a reference basis with which to compare the results of using alum. Since column diameter was found to have little effect on contaminant removal effectiveness in the alum experiments, it was not studied using ferric chloride, and all runs were made in the 12-inch column for convenience. A single level of blanket depth, 7 feet, was used. Coagulant dose levels were set to approximate two values, 129 and 212 mg/l, which correspond to a similar molar Fe^{+++} equivalent as Al^{+++} at 150 and 250 mg/l alum.

Data Correlation

The model chosen to correlate the ferric chloride data included terms representing those variables shown to be important in describing the alum data: pH, coagulant dose (Fe), and upflow velocity (U). Neither diameter nor blanket depth was studied. Owing to the limited data only linear terms were used in the regression model, except for velocity, which is accounted for by both linear and quadratic terms. The regression model is:

$$Y_j = b_{oj} + c_{oj}X_{oj} + \sum_{i=1} a_{ij}X_i + c_{1j}X_1^2$$

where: Y_j = concentration of j measured in the effluent

X_{oj} = concentration of j in influent, mg/l

X_1 = upflow velocity, U, ft/hr

X_2 = ferric chloride dose, Fe, mg/l

X_3 = pH of the wastewater before coagulant addition

X_1^2 = (upflow velocity)^2.

The results of the regression analysis of the data using the above model are shown graphically in Figures 12, 13, 14, 15, and 16. Values of regression coefficients are given in Appendix B. All effects are shown as straight lines as required by the model. The quadratic effect of U^2 does not appear owing to the manner of representation.

Table 5 lists the results of the statistical analysis. The standard deviations are slightly less than those for alum. Although the percent variance removed is markedly greater, this is due in part to the small number of degrees of freedom available (six parameters are fitted to eight data points). The data for the ferric chloride runs are shown in Appendix A.

DIAMETER : 12 INCHES

BLANKET DEPTH : 7 FEET

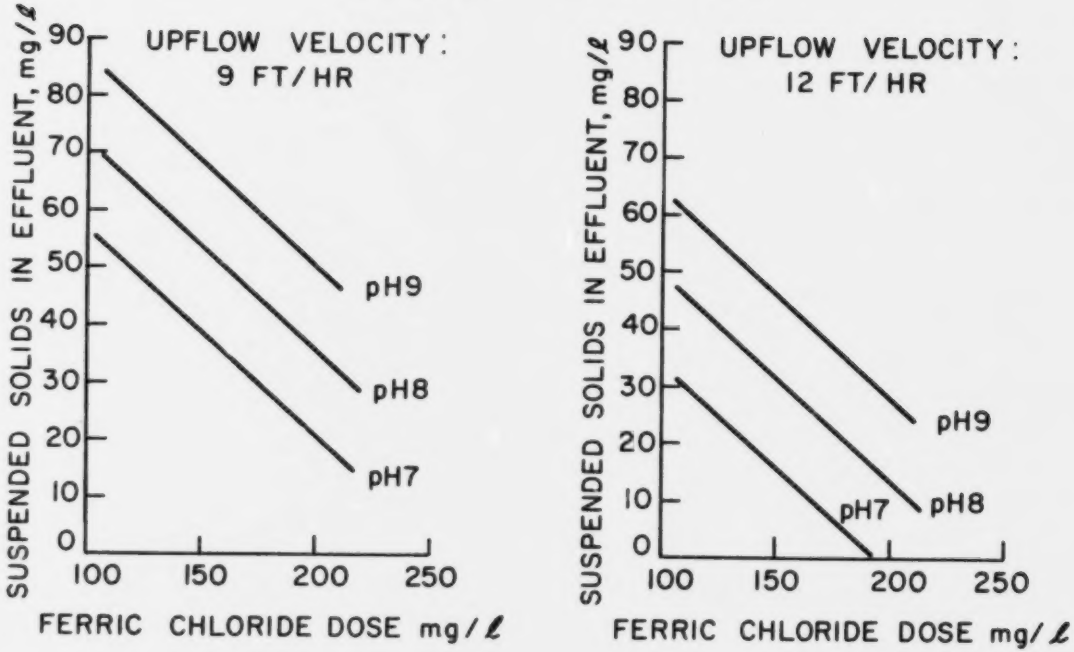

FIG 12 SUSPENDED SOLIDS IN EFFLUENT,

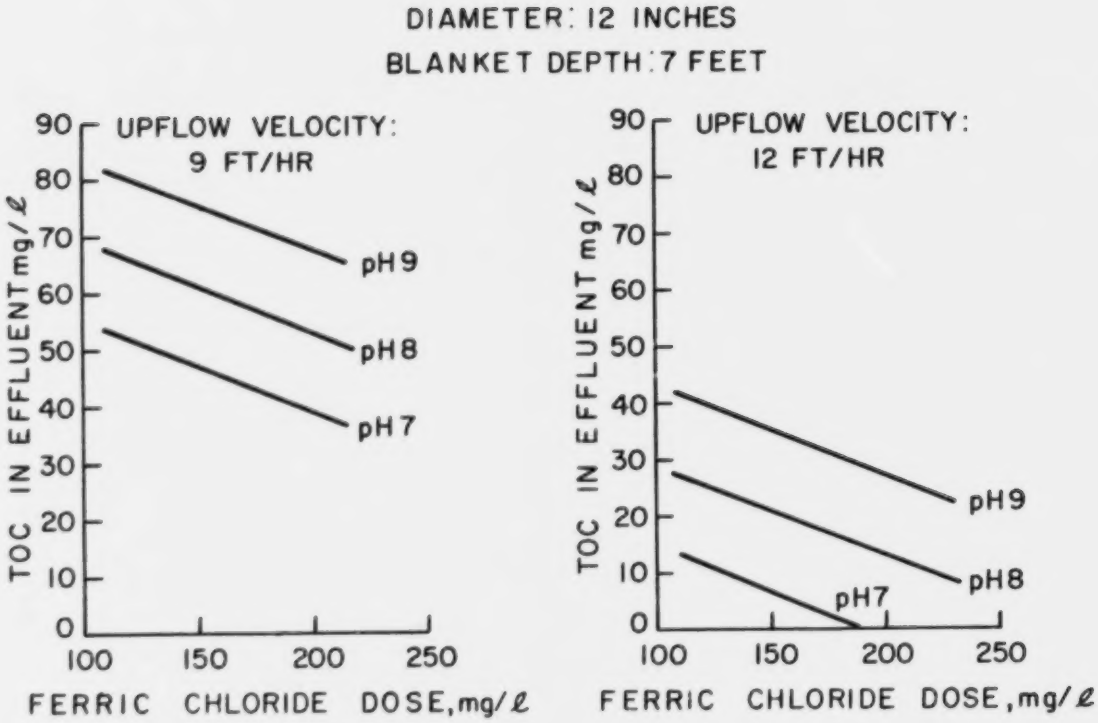

FIG.13 TOTAL ORGANIC CARBON IN EFFLUENT

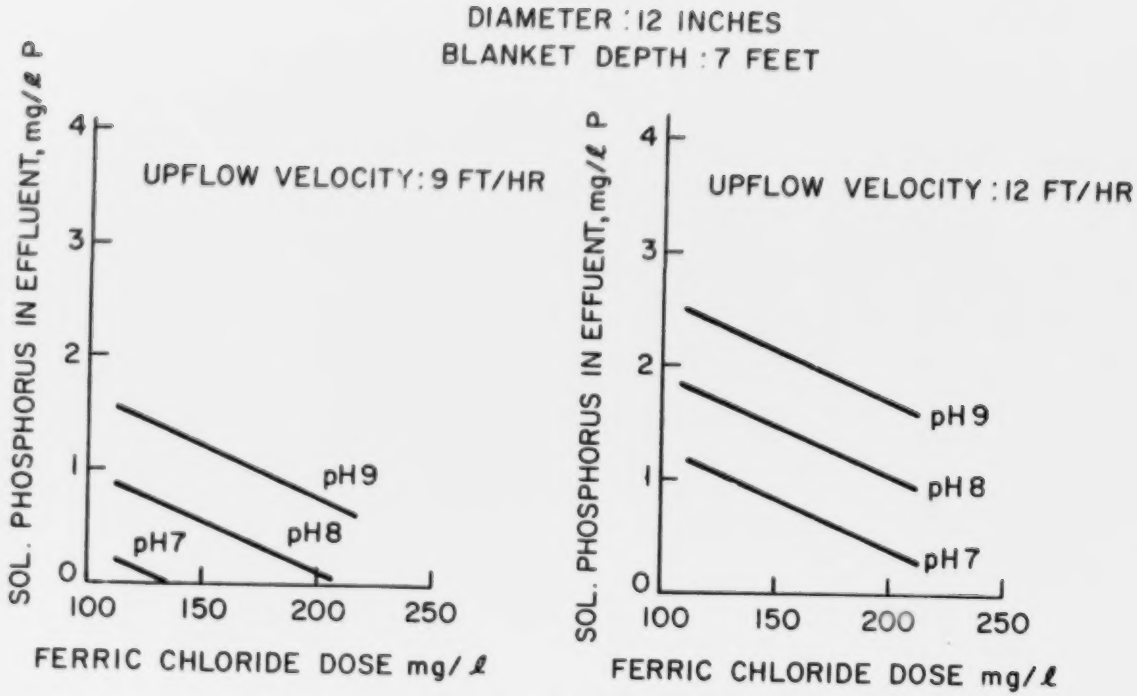

FIG. 14 SOLUBLE PHOSPHORUS IN EFFLUENT

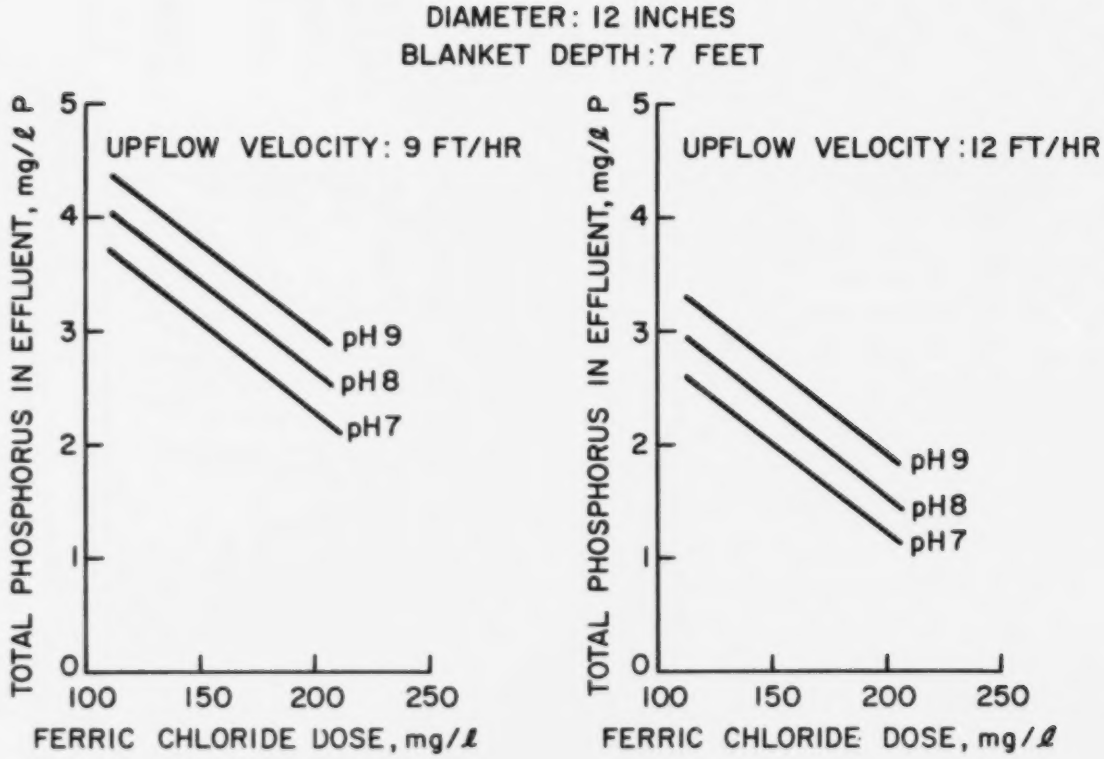

FIG. 15 TOTAL PHOSPHORUS IN EFFLUENT

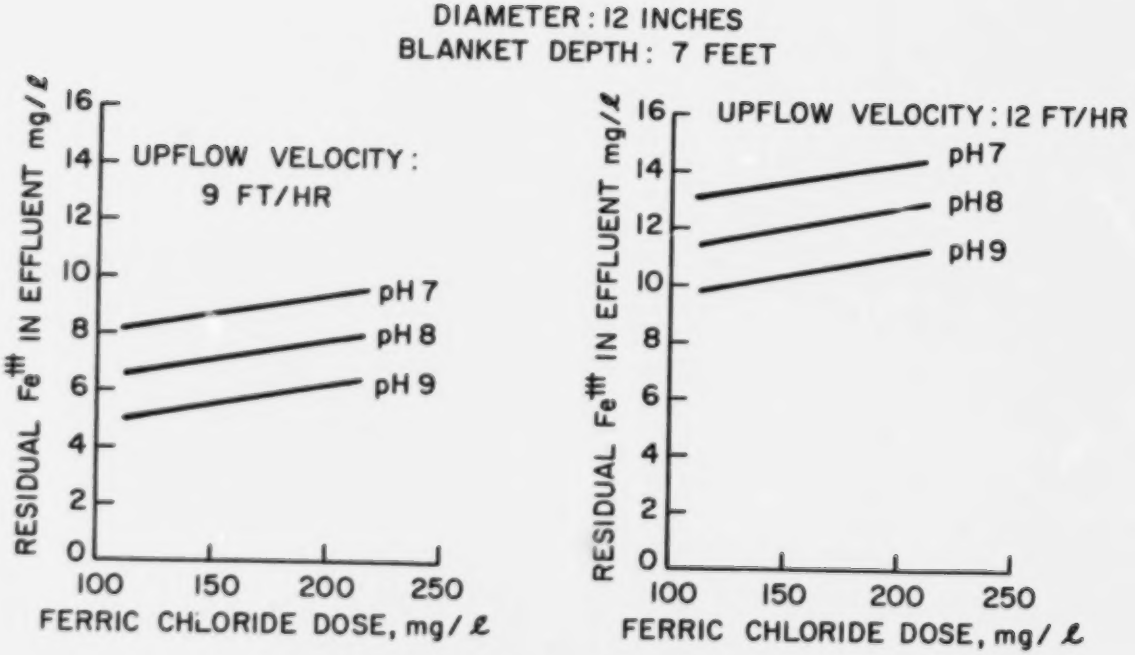

FIG. 16 RESIDUAL Fe^{III} IN EFFLUENT

TABLE 5

Summary of Regression Analysis of Experimental Data
Using Ferric Chloride

Dependent Variable	Percent Variance Removed	Standard Deviation	Influent Effect
Effluent Suspended Solids, mg/l	91	± 3.1	yes
Effluent TOC, mg/l	96	± 2.3	yes
Effluent Soluble Phosphorus, mg/l	92	± 0.61	no
Effluent Total Phosphorus, mg/l	99	± 0.55	yes
Effluent Residual Fe^{+++}, mg/l	60	± 1.9	no
Volume Percent Sludge	4.2%, constant within experimental error		

All correlations except the concentration of residual Fe^{+++} show that increasing coagulant dose and decreasing the pH results in a lower concentration of contaminant in the effluent. The reverse was found for the residual Fe^{+++}.

The correlations show that the concentration of suspended solids, total organic carbon, and total phosphorus all decrease with increasing velocity, while soluble phosphorus increases. Examination of the regression parameters a_1 and c_1 reveals, however, that the effect of velocity is reversed at 12 ft/hr for suspended solids and TOC, at 12.5 ft/hr for soluble phosphorus, and at 13 ft/hr for total phosphorus. Extrapolation of this effect beyond 15 ft/hr is unwarranted. Increasing velocity increases the residual Fe^{+++} in the effluent.

Three of the regression analyses showed a significant effect of contaminant influent concentration on the concentration in the effluent. The following corrections should be added to the effluent predicted from the numerical values shown within the parentheses:

Suspended solids : $+ 0.300(C_s - 181.6)$

Total organic carbon: $+ 0.593(C_c - 131.4)$

Total phosphorus : $+ 0.420(C_p - 11.26)$

where: C_s = influent concentration of suspended solids, mg/l

C_c = influent concentration of total organic carbon, mg/l

C_p = influent concentration of total phosphorus, mg/l, as P.

The correlation for sludge production showed that the sludge production rate was constant at 4.2 volume percent of the influent within the experimental error.

Discussion

It is of interest to compare the results using ferric chloride with those of McLellon et al (14). These investigators studied the coagulation of secondary effluents using ferric chloride in jar test apparatus with automatic titrimeter pH controls. They concluded that the optimum pH for the removal of turbidity and phosphorus was between 5 and 6 for any applied dose of ferric chloride up to about 200 mg Fe^{+++}/l. When the pH of the coagulating mixture was allowed to vary with dose, the tests indicated optimum Fe^{+++} doses depending on the alkalinity and initial turbidity of the wastewater, showing quite clearly that a critical coagulation concentration (ccc) and a critical stabilization concentration (csc) existed and corresponded to the minimum and maximum zeta potential of the wastewater colloids. They showed also that the optimum dose resulted in the optimum pH.

For a secondary effluent having an alkalinity of 130 mg/l, McLellon

showed that the optimum ferric chloride dose for turbidity and phosphorus removal was about 40 to 45 mg Fe^{+++}/1, or 192 to 216 mg $FeCl_3 \cdot 6H_2O$/liter, where phosphorus removal was essentially complete. This dose is close to the higher level dose of the present study (212 mg/1) at essentially the same alkalinity (140 mg/1). Smaller doses would therefore be expected to result in less effective removal as the results of the present study have shown. Increasing initial pH values would also decrease the effectiveness of removal which is also borne out by the present study.

McLellon also showed that the optimum Fe^{+++} dose for COD removal was essentially the same (47 mg Fe^{+++}/1) as for turbidity and phosphorus.

McLellon et al concluded that "pH and the associated buffering effects of alkalinity were primarily responsible for control of the destabilization-restabilization reactions because coagulation of the hydrophilic colloids was the result of the hydrolysis products of the metallic coagulant, which specifically interacted chemically with the ionogenic groups of the colloidal surfaces to form polymeric bridges."

Since the coagulation mechanism is apparently responsible for major contaminant removal as colloids, increasing the effectiveness of coagulation and subsequent flocculation would result in improved removal. This may explain the lower effluent concentrations of suspended solids, TOC, and total phosphorus occurring at higher upflow velocity in the present experiments, since the higher velocity would result in greater shear within the blanket. Soluble phosphorus removal, however, decreases with increasing velocity.

The effect of variables on the residual Fe^{+++} in the effluent may be the result of both solubility and adsorption. The residual Fe^{+++} increases with increasing ferric chloride dose and velocity and decreasing pH. Ferric hydroxides become more soluble as pH is decreased.

Summary of Results of Ferric Chloride Experiments

Table 5 summarizes the results of the statistical analysis and includes the statistics representing the goodness of fit. It should be emphasized that the meaning of significance of the individual terms is not relevant on this correlation owing to the small number of experiments. Moreover, the regression model was chosen to reflect the influences of those variables shown to be significant for alum coagulation.

Table 6 summarizes the treatment effects predicted at the best combination of operating variables within the limited range studied. From the graphs of the correlations this combination is as follows:

Ferric chloride dose	= 212 mg/1
Upflow velocity	= 12 ft/hr
Blanket depth	= 7 ft
pH	= 7.2.

TABLE 6

Summary of Predicted Treatment Effects
Using Ferric Chloride

	Predicted Effluent Concentration mg/l	Average Influent Concentration mg/l	Percent Removed
Suspended Solids	13.6	182	92
Total Organic Carbon	38.5	131	78
Soluble Phosphorus (as P)	0.5	7.0	93
Total Phosphorus (as P)	1.2	11.3	90
BOD_5	68.8	150	54
Residual Fe^{+++}	14.0	1.4	--
Sludge Production	4.2 percent[1/]		

[1/] Volume percent of influent

The value for pH was taken at 7.2 since this was the lowest value actually studied. In the graphs which gave predicted results less than the minimum observed value, the latter value was taken as the prediction and then corrected for influent effect where applicable. The average influent concentrations are also tabulated together with the percent removal based on these influent concentrations. Sludge production was assumed to take the mean observed value of 4.2 volume percent of the influent. The minimum observed value was 3.0 percent.

Comparison of Ferric Chloride Treatment with Alum

Comparison of Tables 4 and 6 reveals that the quality of the effluents from alum and ferric chloride treatment are generally comparable. The notable exception is in the residual coagulant ion concentration. The Al^{+++} concentration is essentially that of the background wastewater concentration (0.95 mg/l) while the Fe^{+++} concentration is ten times background (1.4 mg/l). The amount of this difference is due partially to the fact that variable combinations that were chosen provided a very high residual iron. However, the lowest residual iron concentration found was still 5 mg/l.

It should be noted that the best treatment using ferric chloride occurs at a higher upflow velocity than for alum, 12 ft/hr versus 9 ft/hr, although it was possible to achieve good treatment with both coagulants at 15 ft/hr.

SECTION IX

SLUDGE SETTLING STUDIES

The sludge from an operating clarifier must be processed to reduce its bulk and to render it innocuous. It was therefore appropriate to study the thickening properties of the sludge to see if there were any relationships between the settling velocity and the mode of sludge blanket operation. More explicitly, sludge settling tests and suspended solids analyses were performed

a) to study the character of each sludge

b) to evaluate the effect of changing test run conditions on the sludge behavior

c) to compare the settling characteristics of the undisturbed sludge in the upflow clarifier and the sludge obtained as an operational residue

d) to estimate the area-flow-concentration relationships for a gravity thickener using the solids flux-concentration procedure (7).

Equipment and Procedure

The settling rate of the undisturbed sludge blanket was measured directly in one of the 12-inch diameter Lucite columns. Settling tests on sludge removed from the column were performed in a smaller Lucite cylinder 7.5 inches (18.7 cm) effective diameter and 54 inches (135 cm) in height. These latter dimensions satisfy the minimal requirements of a settling column as recommended by Cole (5) to avoid the interference of diameter and height effects with settling rate.

The residual sludge obtained from the clarifier differed considerably from the sludge comprising the blanket in the operating column:

> The fluidized sludge found in the clarifier consisted of large flocs, had a moderate concentration of suspended solids and good settling properties. In the following this sludge is referred to as "blanket."
>
> The collected sludge was of higher concentration than the blanket owing to some thickening in the bottom of the clarifier. The original large flocs were broken into very small ones when passing through the pipes and fittings. This material is referred to as "sludge."

To illustrate the difference between a blanket and a sludge of the same test run, a height versus time curve is drawn for both slurries in Figures 17 and 18, the slope of the curve being equal to the settling rate of the liquids-solids interface. The settling curve for the sludge follows the

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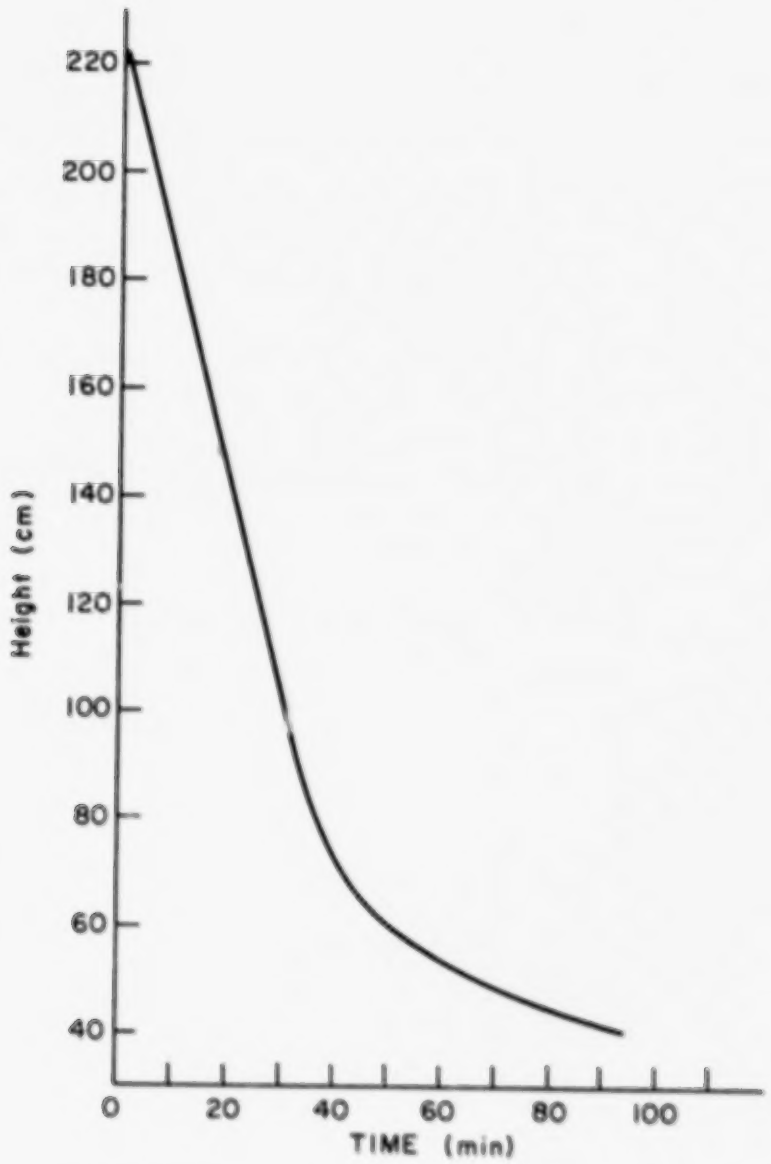

FIG.17 SETTLING CURVE FOR BLANKET OF TEST RUN A1

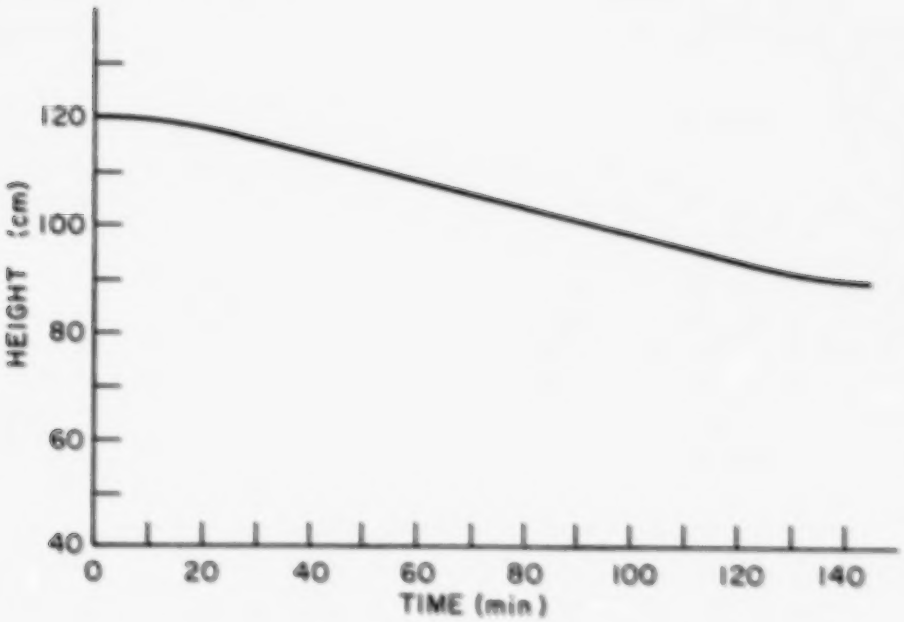

FIG 18 SETTLING CURVE FOR SLUDGE OF TEST RUN A1

settling pattern described as typical for zone settling. For the blanket the pre-flocculation period is missing, since the particles were not disturbed and already developed to the maximum size for given operational conditions.

Settling Test for the Blanket

The settling test for the blanket was performed in the clarifier column itself. Immediately preceding the settling test, samples were withdrawn from the fluidized bed at four levels, and through the bottom tap for the lowest, non-fluidized section of the clarifier. After cutting off the influent stream to the clarifier, the expanded blanket began to settle. The height of the interface and time intervals were recorded, and the settling rate of the blanket was determined as the slope of the straight portion of the curve obtained when height was plotted against time.

Settling Test for the Sludge

The procedure for the settling test for the sludge was the following: The collected waste was mixed thoroughly in the collection container and transferred to four smaller buckets. These were poured rapidly into the 8-inch test cylinder, up to 115 to 130 cm deep, and stirred once more by hand before the interface readings were taken in regular time intervals, depending on the settling velocity, between 1 and 10 minutes. The settling rate was then determined by measuring the slope of the straight portion of the curve of the interface height versus time.

Two sludge samples were taken from the collection bucket while filling the smaller buckets and sent to the laboratory for suspended solids analysis.

Since the volume of sludge required for the settling test, about 10 gallons, was obtained over a variable but relatively long period of time, it had to be of average composition.

Evaluation of the Experimental Data

Over fifty settling tests were performed in the course of this study to find relationships among the settling rates and the characteristics of the blanket, sludge, and the different test run conditions. Half the settling tests were made with dilutions and concentrations of collected sludges, a step required to estimate solids flux-concentration curves needed for thickener design.

The following statistical problems were formulated:

a) Correlation between the suspended solids concentration and position (height above the distributor) in the fluidized blanket.

b) Correlation between the suspended solids concentration in the clarifier and test run conditions (alum dose and upflow velocity).

c) Correlation of the blanket settling rate and the blanket suspended solids concentration, alum dose, and upflow velocity.

d) Correlation of the sludge settling rate and the sludge concentration, alum dose, and upflow velocity.

Problem (a). The data in Table 7 show the suspended solids values obtained by sampling the blanket at different levels, for different test run conditions and for replications of the same test run. Samples of sludge were taken from the sludge discharge line (bottom) and from each of four taps in the side of the column. Tap 1 was located 1 foot from the bottom and the remaining three spaced at 2 foot intervals (see Figure 1). Sludge settling test runs B1 and C4 have incomplete sample sets.

It is obvious from the data that the suspended solids concentration is much higher in the bottom part of the clarifier, which can be explained by the thickening effect in the column below the feed distributor. For the remaining samples, taps 1 to 4, a concentration pattern is not obvious, and for these samples only an analysis of variance was performed, omitting the data from the incomplete sets B1 and C4, since the analysis did not permit missing observations.

Based on prior lab experience with suspended solids analysis, a value of 150 mg/l was adopted for the standard deviation of the suspended solids values for the blanket. Using this value, the analysis of variance showed that the difference in sample means for different blanket positions was not significant at the 5 percent confidence level. This observation is consistent with Tesarik (21), who observed that the concentration of floc throughout the blanket was nearly constant. Tesarik's data showed the concentration to decrease in the lowest 20 percent of the blanket, but his column was different from the ones used in this study in that the entire contents were fluidized and no thickening of sludge was achieved in the bottom.

Because of this finding it was then possible to characterize the whole blanket by a single SS concentration value. Since the sample at any level was shown to be representative of the entire blanket, it was then possible to use the incomplete wample sets, B1 and C4, in further evaluation.

Problem (b). In Table 7, column 8 lists the average SS concentrations from the different heights in the blanket, excluding the bottom sample (column 3). Column 9 is the average of concentrations from column 8 for the given test run replicates. This value is the characteristic blanket

TABLE 7

Data of SS from the Upflow Clarifier

Run Condition* (1)	Run Number (2)	Bottom (3)	Tap 1 (4)	Tap 2 (5)	Tap 3 (6)	Tap 4 (7)	Average of tap 1 - 4** (8)	Average of test run condition** (9)
A	A1	5,898	1,219	667	917	486	822	993
	A2	4,624	1,049	1,098	1,231	802	1,045	
B	B1			994			994	803
	B2		614	697	732	620	666	
	B3	1,363	898	989	904	782	893	
C	C1	849	801	871	846	723	810	915
	C2	752	694	714	812	728	737	
	C3	7,884	1,107	1,024	1,137	1,031	1,075	
	C4			1,187		1,144	1,166	
D	D1	8,192	1,242	1,367	1,363	1,320	1,323	1,323

* Run Condition	Upflow Velocity, U	Chemical Dose, Al	pH
A	9 ft/hr	250 ppm as alum	8
B	12 ft/hr	250 ppm as alum	8
C	12 ft/hr	150 ppm as alum	8
D	9 ft/hr	150 ppm as alum	8

** The SS from bottom samples are not included in the averages.

Remark: All values ± 150 mg/1.

concentration for a test run condition.

From column 8 it is clear that replicates of a test run often resulted in blanket concentrations exceeding the standard deviation of the analysis, and one concludes that the blanket reproducibility is not good. An analysis of variance made on the average values given in column 9 showed that the differences were not statistically significant. The differences in upflow velocity between runs may have been too small to result in a detectable difference due to blanket expansion. For example, the formula of Richardson and Zaki (17) which Brown and LaMotta (2) have shown applicable to alum flocs would predict only 5 or 6 percent change in flow concentration if the ratio in upflow velocities were only 9/12.

Problem (c). Table 8 presents the measured settling rate of the blanket together with the SS concentration of the blanket and the test run conditions (upflow velocity, U, and alum dose, Al). The remaining test run conditions, pH and blanket depth, were held constant at pH 8 and 7 feet, respectively.

Several forms of statistical relationships were tried between the settling rate (SR) as the dependent variable and SS, U, and Al as the independent variables. The most successful was the following determined by a regression analysis:

$$\log SR = 0.1457 + 0.0003\ SS + 0.0286\ U + 0.0002\ Al\ . \qquad (9\text{-}1)$$

This regression formula accounted for 56 percent of the variations in the settling rates observed, with the upflow velocity accounting for 47 percent.

The hypothesis that the settling rate was no different from the upflow velocity was further tested by analysis of the regression equation:

$$\log SR = a + b \log U\ . \qquad (9\text{-}2)$$

It was found that (a) was not statistically different from zero and (b) was not different from 1.0 at the 95 percent confidence level; and therefore, the settling rate of the blanket was not different from the upflow velocity. This result is consistent with the findings of Richardson and Zaki (17) for different types of particles and supports the conclusion of Brown and LaMotta (2), confirming the application of Richardson and Zaki to alum flocs.

It was concluded that the significant variable affecting the blanket settling rate is the upflow velocity.

TABLE 8

Observed Parameters of the Clarifier

Run Number	Blanket Settling Rate (SR)		Blanket Concentration (SS)	Upflow Velocity (U)	Chemical Dose (Al)
	cm/min	ft/hr	mg/l	ft/hr	mg/l as alum
A_1	3.96	7.8	822	9	250
A_2	5.0	9.85	1,045	9	250
B_1	5.13	10.2	994	12	250
B_2	5.46	10.8	666	12	250
B_3	4.85	9.6	893	12	250
C_2	4.64	9.1	737	12	150
C_3	5.74	11.4	1,075	12	150
C_4	5.12	10.1	1,166	12	150
D_1	4.10	8.1	1,323	9	150

Problem (d). Table 9 gives the settling rates and SS concentrations for the sludge produced during the test run conditions shown. As in the study of the blanket settling rates, pH and blanket depth have been held constant.

An analysis similar to that of Problem (c) was made with the result that the following correlation accounts for 96 percent of the variation in the settling rate of the sludge:

$$SR = 7.452 - 0.001\ SS - 0.266\ U - 0.005\ Al\ . \qquad (9\text{-}3)$$

Using the logarithm of the settling rate results in a slightly inferior correlation, accounting for 88 percent of the variation:

$$\log SR = 3.790 - 0.001\ SS - 0.207\ U - 0.002\ Al\ . \qquad (9\text{-}4)$$

It was also determined that the SS term in (9-3) accounts for about 72 percent of the variation, and in (9-4), 77 percent of the variation. The remainder accounted for by the upflow velocity and the alum dose is probably the result of a slight change in floc character.

It was concluded that clarifier operating conditions had no practical effect on the settling rate of the sludge. It must be borne in mind that the test runs studied were made over several weeks' time and that differences in the wastewater quality, particularly the concentration of suspended solids, probably are responsible for much of the variability in the character of the sludge.

Sludge Thickener Design

Consideration of the means of disposing of sludge from a clarifier leads naturally to the question of determining the thickener area required to achieve a thickened sludge of required solids concentration. This section presents the results of a study to estimate the area of a thickener from the settling properties of sludge produced by the clarifier. The most direct means of doing this is by the solids flux-concentration method (7) which requires determination of the settling rate as a function of solids concentration. Having found the settling rate as a function of concentration, a flux-solids concentration curve is calculated by plotting the product (solids concentration) × (settling rate) versus solids concentration. For a given underflow solids concentration, the minimum flux is then determined as the intercept of the straight line through the underflow concentration tangent to the flux curve. The area required is then found from the relationship:

$$A = \frac{Q_o C_o}{G_{min}} \qquad (9\text{-}5)$$

TABLE 9

Observed Parameters of Sludge Tests

Run Number	Sludge Settling Rate (SR) cm/min	ft/hr	Sludge Concentration (SS) mg/l	Clarifier Upflow Velocity (U) ft/hr	Chemical Dose (Al) ppm
A SR	0.25	0.45	4,618	9	250
A SR2	0.05	0.10	4,999	9	250
B S	1.69	3.33	1,559	12	250
B S1	1.75	3.45	1,559	12	250
C SR	2.38	4.70	752	12	150
C SR2	0.04	0.08	4,948	12	150
D S	2.63	5.19	2,272	9	150
D SR	0.54	1.06	5,411	9	150
D SR3	0.02	0.04	8,635	9	150

where: A = thickener cross-sectional area, L^2

Q_o = influent rate to the thickener, L^3/θ

C_o = influent solids concentration, M/L^3

G_{min} = minimum solids flux, $M/L^2\theta$.

The method assumes an overflow having zero suspended solids. A typical flux-concentration curve showing the required construction is given in Figure 19.

The data for the settling rate concentration curves were obtained by repeated measurements of the settling rate at different concentrations of sludges produced from test runs having the operating conditions of experiments A and B (cf. Table 7). These concentrations were varied by removing part of the supernatant after each settling test and remixing the remaining sludge.

Since the settling-remixing operations took considerable time, the question of changing settling properties arose. Two sludges were reused two and three times, respectively; and the settling rates were measured with the following result:

Settling Test	Settling Rate	Settling Test	Settling Rate
Ba	1.69 cm/min	BS1	0.43 cm/min
Ba'	1.75 cm/min	BS2	0.46 cm/min
		BS3	0.46 cm/min

It was concluded that no substantial difference in settling rates resulted from reuse and aging; and therefore, the remixing procedure could be used with confidence.

The data for the settling tests are listed in Appendix C and are plotted in Figure 20. Test runs A and B differed only in upflow velocity, and since the settling rates for sludge did not appear to depend on velocity in a significant way, a correlation of settling rate with suspended solids concentration was obtained by regression analysis. The preferred correlation was in the form:

$$\log SR = 0.6252 - 0.000300\ SS \qquad (9\text{-}6)$$

which accounted for 73 percent of the variation.

The form of equation (9-6) is characteristic to many sludges and lends itself to easy mathematical analysis, allowing the flux-area-relationship

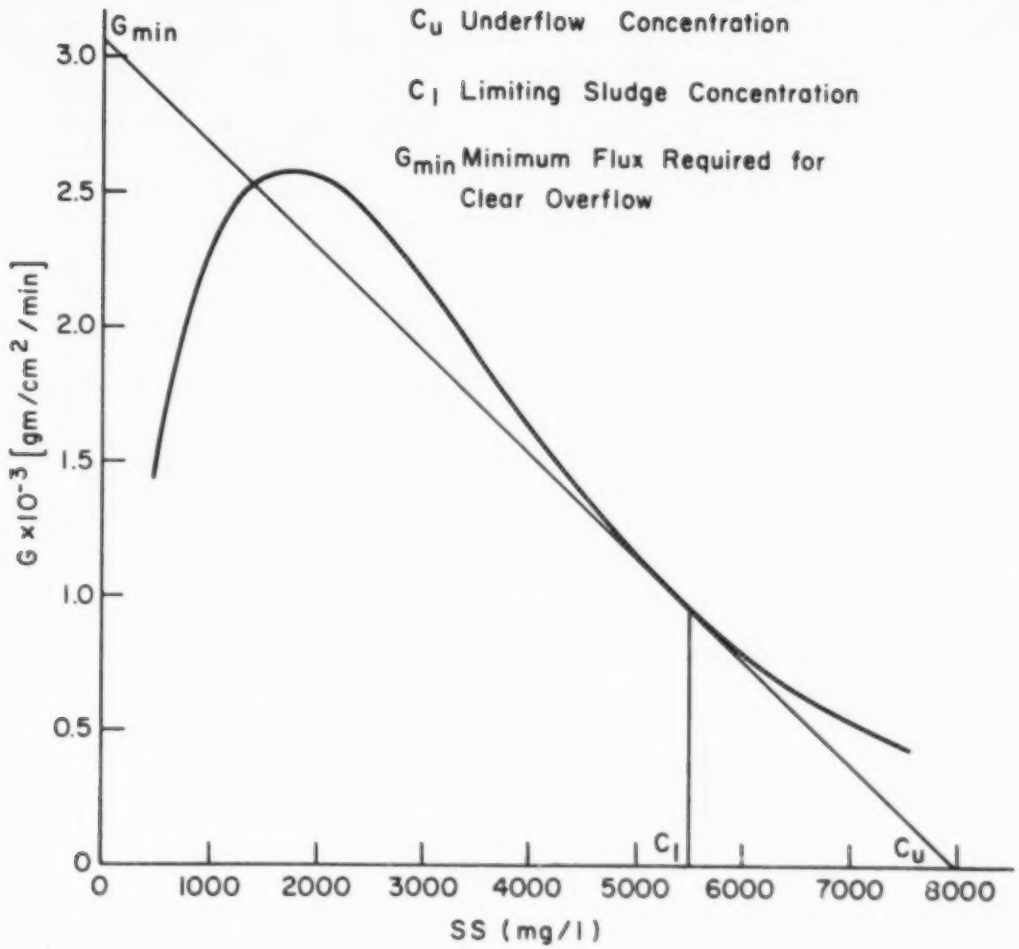

FIG.19 FLUX CURVE

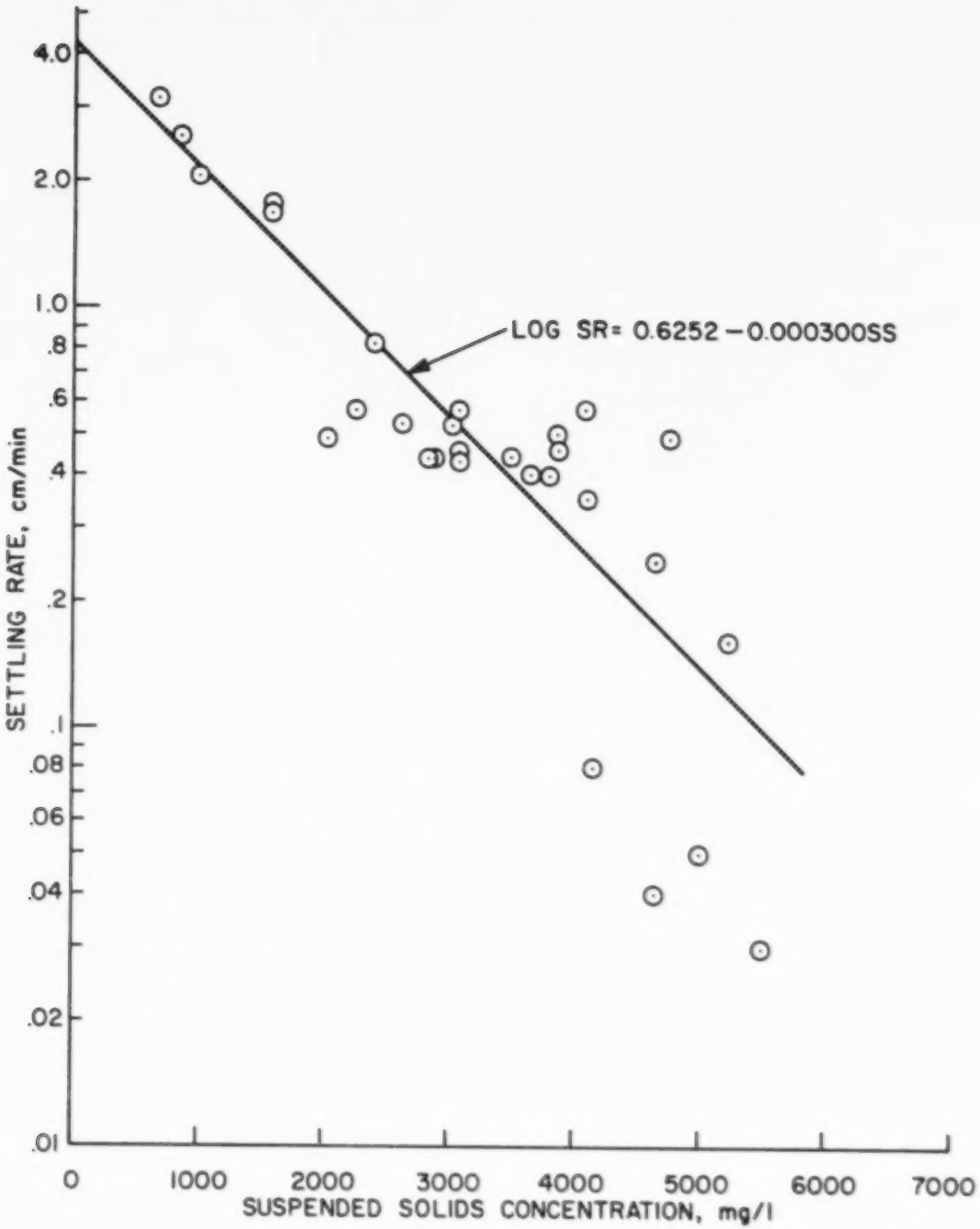

FIG.20 SLUDGE SETTLING RATES VS SUSPENDED SOLIDS CONCENTRATION

to be expressed by a relatively simple formula. To derive this formula, note that in Figure 19, the flux curve, the straight operating line must be tangent at some value of concentration, C_1. The equation for the operating line is:

$$G = G_{min}\left(1 - \frac{C}{Cu}\right) \tag{9-7}$$

and its slope is seen to be $-G_{min}/Cu$.

From equation (9-6), putting $C \equiv SS$, the flux curve equation is simply:

$$G = a_o C e^{-b'C}, \ \frac{gm}{cm^2 min} \tag{9-8}$$

where $a_o = e^{(2.303)(.6252)} = 4.23$ cm/min

$b' = (2.303)(.000300)(10^6)$, cm^3/gm

$C = gm/cm^3 = (mg/l \times 10^{-6})$

The condition of tangency at C_1 is thus:

$$a_o e^{-b'C_1}(1 - b'C_1) = -\frac{G_{min}}{Cu} \tag{9-9}$$

$$a_o C_1 e^{-b'C_1} = G_{min}\left(1 - \frac{C_1}{Cu}\right) \tag{9-10}$$

Solving equations (9-9) and (9-10) simultaneously gives the value of C_1 as:

$$C_1 = Cu\left[\frac{b'Cu + \sqrt{(b'Cu)^2 - 4b'Cu}}{2b'Cu}\right] \tag{9-11}$$

Solving (9-10) for G_{min} gives:

$$G_{min} = \frac{a_o C_1 e^{-b'C_1}}{1 - C_1/Cu} \tag{9-12}$$

and from equation (9-5)

$$\frac{A}{Q_o C_o} = \frac{1}{G_{min}} = \frac{(1 - C_1/Cu)}{a_o C_1} e^{b' C_1}, \quad \frac{cm^2 min}{gm} \qquad (9\text{-}13)$$

Figure 21 shows A/Q_oC_o plotted against Cu for values of Cu in mg/l and A/Q_oC_o in $\underline{(ft^2)(1000\ gal./day)(mg/l)}$. To illustrate the use of Figure 21, consider the problem of estimating the area of thickener required to produce a thickened sludge of SS concentration of 10,000 mg/l from a dilute sludge of SS concentration of 1000 mg/l if the sludge volume rate is 400,000 gal./day. At Cu = 10,000, $A_o/Q_oC_o = 4.1 \times 10^{-3}$, and

$$A = 4.1 \quad 10^{-3} \quad 400 \quad 1000 = 1640\ ft^2.$$

A thickener with circular cross section would need to be 46 feet in diameter.

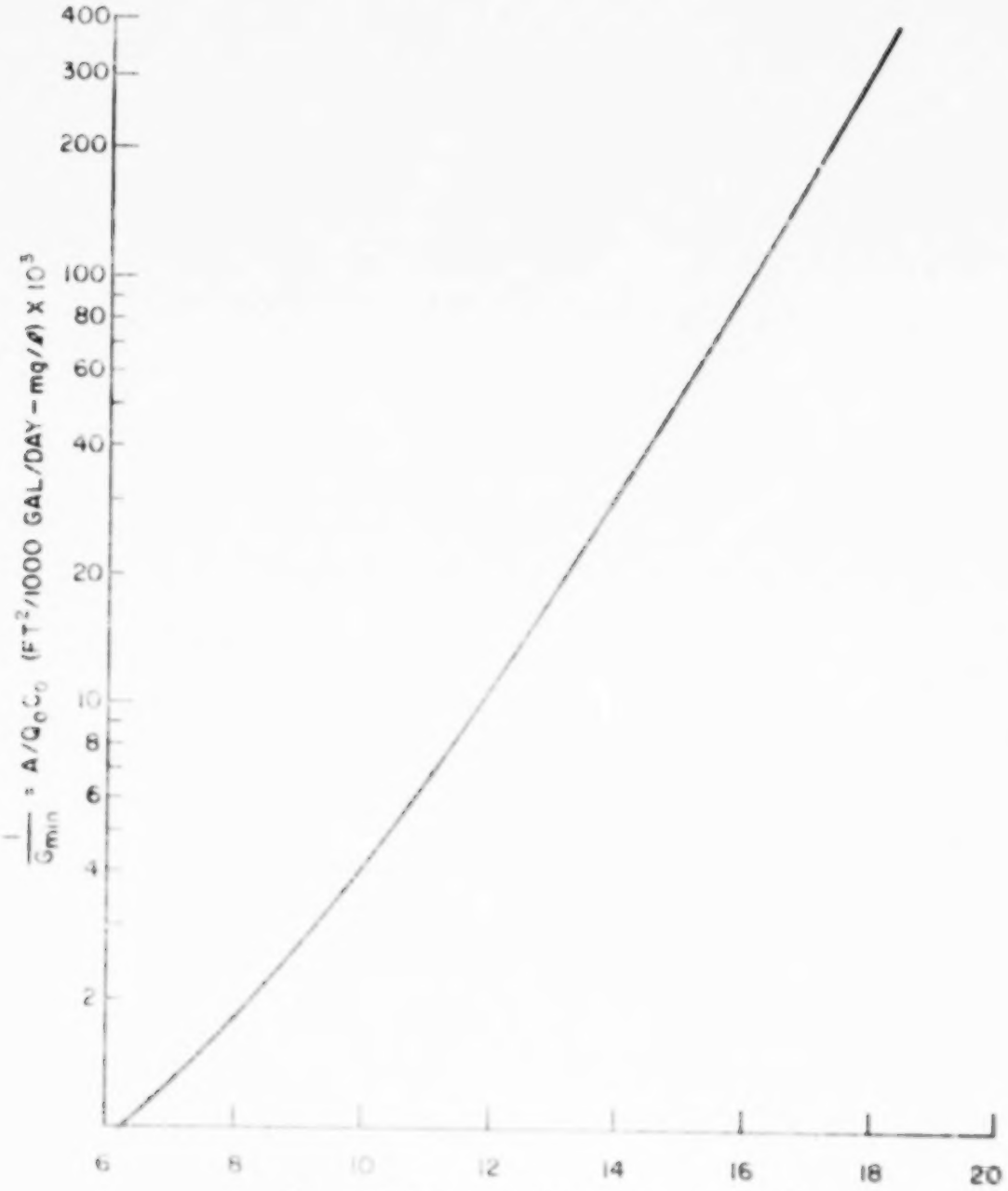

FIG 21 RECIPROCAL MINIMUM SOLIDS FLUX VS THICKENER SOLIDS CONCENTRATION

SECTION X

EXPERIMENT USING ACTIVATED SILICA AS A SLUDGE THICKENING AID

A controlled experiment was made in the 12-inch diameter columns using activated silica with alum to determine the effect of activated silica in thickening the sludge. Operating conditions were chosen to represent a situation normally producing a high sludge volume rate so that a significant effect in reducing sludge volume could be most apparent. These conditions were

$$U = 15 \text{ ft/hr}$$
$$L = 7 \text{ ft}$$
$$Al = 200 \text{ mg/l}$$
$$pH = 7.8.$$

Philadelphia Quartz Company "N"-type sol was activated according to the manufacturer's instructions using sodium bicarbonate. A dose of 30 mg/l was used. The activated sol was introduced into the feed line at the same point as the alum solution in one of the 12-inch columns. The other column was operated in an identical manner with the same wastewater but with no silica addition.

Table 10 lists the average influent, effluent and sludge analyses for the control and the corresponding data using silica. As can be seen, the effects of using the silica are substantial, the major effect being the increased concentration of sludge constituents in the silica run. The sludge volume is 57 percent of the control value.

TABLE 10

Treatment Effects Using Alum with Activated Silica[1/]

Parameter	Sewage	With Silica		Control	
		Effluent	Sludge	Effluent	Sludge
Suspended Solids	165 mg/l	12	1,348	18	796
Total Organic Carbon	193	34	404	35	286
Soluble Phosphorus	8.7	0.8	--	1.0	--
Total Phosphorus	13.3	1.4	45.5	1.2	37.5
Residual Al^{+++}	2.9	1.4	105	1.5	57
BOD_5	126	29	--	38	--
Volume Percent Sludge	---	19.4		33.6	

[1/] All results in mg/l except sludge volume

SECTION XI

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SECTION XII

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SECTION XIII

PUBLICATIONS AND PATENTS

No patents or publications have been produced as a result of this project.

SECTION XIV

APPENDICES

Page No.

A. Test Run Data

Summary of Test Run Data Using Alum

Table A-1: Measured Values of Independent Variables . . . 86

Table A-2: Measured Values of Dependent Variables 88

Summary of Test Run Data Using Ferric Chloride

Table A-3: Measured Values of Independent Variables . . . 91

Table A-4: Measured Values of Dependent Variables 92

B. Numerical Values of Coefficients In Regression Model

Table B-1: Alum Coagulant 94

Table B-2: Ferric Chloride Coagulant 97

C. Data for Thickener Design 98

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TABLE A-1

Summary of Test Run Data Using Alum

Measured Values of Independent Variables

No.	Diameter inches D	Upflow Velocity ft/hr U	Alum Dose mg/l Al	Depth ft L	pH
1	12	8.6	258	7.0	8.0
2	12	9.2	315	7.0	8.7
3	12	9.4	185	7.0	8.0
4	12	9.0	259	2.75	7.9
5	12	8.9	217	3.0	8.0
6	12	11.7	238	7.0	8.0
7	12	11.6	294	7.0	7.9
8	12	12.0	214	7.0	8.0
9	12	12.2	239	3.0	8.0
10	12	11.8	232	3.3	8.0
11	12	12.1	150	3.0	8.0
12	12	12.4	125	3.0	8.0
13	12	12.1	216	7.3	8.0
14	12	12.6	252	7.2	8.0
15	12	9.2	191	3.1	8.0
16	12	9.0	273	7.0	8.0
17	24	8.7	260	7.0	8.0
18	24	9.1	324	3.3	8.0
19	24	11.6	300	7.3	7.9
20	24	11.9	199	3.5	8.0
21	24	12.0	120	3.0	8.0
22	24	13.7	136	3.5	8.0
23	24	11.9	187	7.0	8.0
24	24	9.0	282	3.0	8.0
25	24	9.0	120	3.5	8.0
26	24	9.0	150	7.0	8.0
27	24	8.8	242	7.0	7.4
28	24	9.2	235	3.0	7.4
29	24	12.0	255	7.0	7.1
30	24	12.0	268	2.25	7.2
31	24	12.1	158	7.0	7.3
32	24	8.9	125	3.0	7.2
33	24	9.8	279	7.0	9.0
34	24	11.9	222	3.0	9.0
35	12	9.1	204	7.0	7.4

TABLE A-1 (cont.)

No.	Diameter inches D	Upflow Velocity ft/hr U	Alum Dose mg/l Al	Depth ft L	pH
36	12	12.0	211	0.75	7.3
37	12	12.6	216	3.0	7.2
38	12	12.2	150	2.5	7.3
39	12	8.8	153	7.0	7.5
40	12	9.1	208	7.1	9.0
41	12	8.9	242	3.0	9.0
42	12	9.1	183	3.0	9.0
43	12	12.0	412	7.25	9.0
44	12	12.0	413	7.0	9.0
45	12	13.7	162	2.6	9.0
46	12	14.9	216	5.0	8.2
47	24	14.5	178	5.0	8.5
48	12	6.0	321	5.0	8.2
49	24	6.0	150	5.0	8.0
50	12	10.0	308	5.0	8.5
51	24	10.5	268	5.0	8.0

TABLE A-2

Summary of Test Run Data Using Alum

Measured Values of Dependent Variables

No.	Susp. Solids in effluent mg/l	Susp. Solids in sewage mg/l	TOC in effluent mg/l	TOC in sewage mg/l	Soluble P in effluent mg/l	Soluble P in sewage mg/l	Total P in effluent mg/l	Total P in sewage mg/l	Al^{+++} in effluent mg/l	Al^{+++} in sewage mg/l	Volume Percent Sludge	BOD in sewage mg/l	BOD in effluent mg/l
1	18.0	208	41.0	201	0.65	10.5	3.20	15.2	1.30	1.20	9.14	--	--
2	18.0	328	50.0	197	0.80	8.60	3.20	15.2	2.60	10.0	6.25	--	--
3	18.0	213	41.0	192	0.35	8.50	1.45	14.0	1.30	0.85	35.1	--	--
4	34.0	274	62.0	224	1.70	10.6	2.95	12.6	4.60	1.00	9.1	--	--
5	24.0	210	36.0	166	0.45	7.70	2.95	12.6	6.60	1.55	9.96	--	--
6	14.0	252	49.0	176	0.60	9.50	3.60	16.3	1.50	2.20	24.7	--	--
7	13.0	198	19.0	102	0.10	4.90	1.20	7.25	1.60	2.60	13.3	150	37
8	10.0	195	28.0	87	0.50	7.40	0.80	8.95	1.10	0.50	23.1	216	45
9	47.0	198	25.0	186	0.45	4.90	2.20	7.25	5.00	2.60	10.3	150	77
10	37.0	196	24.0	89	2.00	8.30	2.00	8.25	5.20	0.20	20.8	150	83
11	44.0	210	23.0	115	0.10	5.90	2.10	10.0	3.10	0.50	2.50	224	24
12	40.0	142	24.0	151	0.10	3.40	1.30	5.55	3.10	0.10	2.50	174	35
13	20.0	196	19.0	135	0.45	5.90	0.85	8.25	0.55	0.20	24.1	150	24
14	22.0	161	22.0	165	0.30	5.60	0.80	8.75	0.70	0.50	25.6	156	28
15	38.0	161	22.0	102	0.55	5.60	1.45	8.75	2.55	0.50	6.52	156	29
16	14.0	180	39.0	113	1.30	8.60	2.15	12.40	7.80	0.90	11.0	198	59
17	6.5	198	22.0	107	0.20	4.90	1.60	7.25	1.20	2.55	7.00	150	37
18	88.0	161	23.0	214	1.05	5.60	1.60	8.75	5.50	0.50	7.70	156	26
19	42.0	196	27.0	186	0.50	5.85	1.95	8.25	5.60	0.20	7.2	150	37
20	25.0	195	27.0	214	1.15	7.40	1.50	8.95	3.50	0.50	9.00	216	36

TABLE A-2 (cont.)

No.	Susp. Solids in effluent mg/l	Susp. Solids in sewage mg/l	TOC in effluent mg/l	TOC in sewage mg/l	Soluble P in effluent mg/l	Soluble P in sewage mg/l	Total P in effluent mg/l	Total P in sewage mg/l	Al^{+++} in effluent mg/l	Al^{+++} in sewage mg/l	Volume Percent Sludge	BOD in sewage mg/l	BOD in effluent mg/l
21	56.0	210	29.0	59.0	0.30	5.90	3.10	10.0	3.40	0.50	26.4	224	38
22	17.0	195	30.0	186	0.8L	7.40	1.20	8.95	2.00	0.50	17.2	216	38
23	36.0	112	30.0	70.0	0.10	1.85	0.95	4.50	4.60	0.75	3.00	60	14
24	42.0	210	28.0	52.0	0.30	5.90	2.10	10.0	3.20	0.50	13.4	224	32
25	40.0	123	4.50	214	0.30	4.05	2.40	6.20	3.40	0.20	6.00	66	38
26	23.0	84.0	8.00	102	0.10	1.60	0.95	2.90	4.10	0.05	1.70	69	17
27	10.0	246	28.0	183	0.45	6.95	1.20	10.4	1.25	0.20	21.1	204	66
28	53.0	246	31.5	183	1.05	6.95	4.15	10.4	4.75	0.20	9.60	204	56
29	33.5	64.0	12.5	41.0	0.50	2.30	1.10	3.90	5.80	0.10	4.90	156	35
30	37.5	63.0	8.50	47.0	0.60	4.90	1.40	5.20	4.20	0.45	6.60	--	10
31	29.0	63.0	8.00	47.0	0.30	4.05	1.20	5.2	2.75	0.45	2.90	51	14
32	29.0	64.0	9.50	41.0	0.10	2.30	1.40	3.90	2.90	0.10	4.90	165	38
33	30.0	263	39.0	136	1.55	9.85	2.75	12.8	3.55	0.70	7.20	174	71
34	92.0	156	57.0	128	0.90	8.90	5.10	12.6	7.70	0.45	12.6	138	74
35	6.50	246	26.0	183	0.35	6.95	0.80	10.4	0.45	0.45	5.10	204	42
36	17.5	50.5	6.00	31.0	0.10	2.30	0.45	3.75	0.45	0.10	2.80	42	8
37	32.5	50.0	9.00	31.0	0.10	2.30	0.95	3.80	4.20	0.10	3.90	42	9
38	90.0	200	11.0	138	4.30	5.70	6.10	8.60	0.10	0.50	2.90	--	--
39	76.0	235	57.0	195	3.40	8.10	5.80	12.4	5.50	0.10	4.20	96	41
40	10.0	173	43.0	143	0.45	5.50	1.15	10.5	2.80	1.10	5.20	--	--
41	27.0	262	44.0	235	0.60	8.20	1.60	13.2	4.20	1.60	8.40	--	--
42	94.0	165	64.0	165	4.30	9.10	8.40	16.1	10.9	1.45	5.60	--	--
43	11.0	263	27.0	136	0.40	9.85	1.30	12.8	0.60	0.70	11.9	174	77
44	19.0	224	31.0	160	0.55	10.7	1.05	12.8	1.15	1.25	9.60	168	52
45	178	243	101	128	7.80	8.90	12.2	12.6	11.6	0.50	3.60	138	114

TABLE A-7 (cont.)

No.	Susp. Solids in effluent mg/l	Susp. Solids in sewage mg/l	TOC in effluent mg/l	TOC in sewage mg/l	Soluble P in effluent mg/l	Soluble P in sewage mg/l	Total P in effluent mg/l	Total P in sewage mg/l	Al^{+++} in effluent mg/l	Al^{+++} in sewage mg/l	Volume Percent Sludge	BOD in sewage mg/l	BOD in effluent mg/l
46	23.0	161	17.0	103	0.50	8.00	1.30	10.3	2.60	0.80	31.0	129	51
47	11.0	91.0	11.0	65.0	0.10	6.10	1.10	6.70	2.80	0.80	12.0	81	8
48	5.50	161	14.0	103	0.10	8.60	2.00	10.3	1.45	0.80	4.60	129	68
49	12.0	100	10.7	71.0	0.70	5.20	0.70	6.50	1.20	0.80	4.20	79.5	12
50	19.0	91.0	14.5	65.0	0.10	4.10	0.85	4.70	3.10	0.80	28.6	81	11
51	28.0	100	13.0	71.0	0.10	5.20	1.10	6.50	4.10	0.80	6.10	79.5	17

TABLE A-3

Summary of Test Run Data Using Ferric Chloride

Measured Values of Independent Variables

No.	Upflow Velocity ft/hr U	Ferric Chloride Dose mg/l	pH
1	15.1	272	8.1
2	15.0	204	7.2
3	12.3	240	8.3
4	12.0	228	7.3
5	12.1	156	8.4
6	12.2	141	7.3
7	9.0	185	8.0
8	9.04	168	7.2

TABLE A-1

Summary of Test Run Data Using Ferric Chloride

Measured Values of Dependent Variables

No.	Susp. Solids in effluent mg/l	Susp. Solids in sewage mg/l	TOC in effluent mg/l	TOC in sewage mg/l	Soluble P in effluent mg/l	Soluble P in sewage mg/l	Total P in effluent mg/l	Total P in sewage mg/l	Fe^{+++} in effluent mg/l	Fe^{+++} in sewage mg/l	Volume Percent Sludge	BOD in sewage mg/l	BOD in effluent mg/l
1	39	159	21	97	0.3	8.2	2.0	11.8	6	1	4.4	150	75
2	16	187	22	112	0.3	7.3	2.5	16.6	5	1	4.5	168	44
3	38	263	42.3	170	1.2	7.9	1.7	11.5	11	1.7	4.69	131	47
4	7	204	18	166	0.45	6.1	0.75	10.6	7.5	2	3.7	136	38
5	45	172	60	179	2.35	8.1	3.1	11.8	9	1.5	3.45	111	65
6	41	197	32.5	158	1.1	5.75	2.4	10.1	8	2	5.2	156	60
7	38	84	25.5	59.5	0.85	5.1	1.35	5.1	7.5	1	4.06	180	36
8	59	187	43	112	0.3	7.25	5.2	14.6	14	1	3	168	59

APPENDIX 3

TABLES OF REGRESSION MODEL COEFFICIENTS

The following tables list the numerical values of the coefficients in the regression formulas as shown.

Numerical values are presented in floating point form for convenience in tabulation. Ten significant figures are reported and should be retained to minimize round-off error during computation. The results reported in the text were computed retaining all ten significant figures.

TABLE B-1

Numerical Values of Coefficients in Regression Model[1/]
Alum Coagulant

$$Y_j = b_{oj} + c_{oj}X_{oj} + \sum_{i-1}^{5} a_{ij}X_i + \sum_{\substack{i,k=1 \\ i\neq k}}^{5} a_{ijk}X_iX_k + \sum_{i=2}^{5} c_{ij}X_1^2 + d_{1j}X_1X_3X_4$$

$$+ d_{2j}X_2X_4X_5 + d_{3j}X_1X_2X_3X_4X_5$$

Y_j = effluent concentration, mg/l
X_1 = column diameter, D, inches
X_2 = upflow velocity, U, ft/hr
X_3 = coagulant dose, Al, mg/l
X_4 = blanket depth, L, ft
X_5 = pH before coagulant addition
X_{oj} = concentration of j in influent, mg/l

	Effluent Concentration Suspended Solids j = 1	Total Organic Carbon j = 2	Total Phosphorus j = 3	Residual Al^{+++} j = 4	Volume Percent Sludge j = 5
b_o =	2.401546952E3	1.313209375E3	1.556026732E2	6.165965239E1	-7.011041523E2
c_o =	6.750828988E-2	7.496236799E-2	3.681840453E-1	1.542031547E-1	-3.327649793E-3
a_{1j} =	1.926031772E0	4.225776396E0	6.074711403E-1	1.679361330E0	6.593180037E0
a_{2j} =	-1.052067640E2	-1.015475574E2	-5.069301940E0	-4.268367818E0	2.163806100E1
a_{3j} =	1.745588551E0	5.645463167E-1	2.417790192E-1	3.862958669E-1	8.220314923E-2
a_{4j} =	-2.199752526E2	-1.243209470E2	-1.026258881E1	-4.718036146E0	8.294901443E1
a_{5j} =	-5.468436417E2	-2.363326236E2	-4.032835919E1	-2.656202754E1	1.197318401E2

TABLE B-1 (cont.)

	Effluent Concentration Suspended Solids j = 1	Total Organic Carbon j = 2	Total Phosphorus j = 3	Residual Al^{+++} j = 4	Volume Percent Sludge j = 5
a_{12j} =	-1.124878379E0	-2.333677117E-2	-7.957952689E-2	-6.877459572E-2	9.805384525E-2
a_{13j} =	3.248916887E-2	7.956793165E-4	8.944425800E-4	-3.347116684E-4	-2.978614228E-2
a_{14j} =	6.546904534E-1	-2.742262237E-1	8.715783150E-2	3.242490680E-2	-1.496716122E0
a_{15j} =	3.463991390E-1	-5.342339549E-1	-1.530079432E-2	-1.359683740E-1	-1.684088129E-2
a_{23j} =	-6.768911337E-2	-1.386573337E-2	-6.135029152E-3	-4.224053098E-3	1.427994130E-2
a_{24j} =	2.927582096E1	1.386364686E1	1.220129250E0	1.317492316E0	-5.959921912E0
a_{25j} =	1.999163754E1	1.398587744E1	1.140034594E0	1.201353847E0	-2.884657222E0
a_{34j} =	1.536683211E-2	-1.368997021E-2	4.526250503E-3	-3.383898144E-3	-1.102133105E-1
a_{35j} =	-3.172370866E-1	-3.976917707E-2	-2.949983924E-2	-4.458780550E-2	5.200294512E-2
a_{45j} =	3.044240732E1	1.562904639E1	1.480293490E0	1.310640570E0	-8.581309540E0
c_{2j} =	-8.748592219E-1	-2.653454709E-1	-5.868436815E-2	-1.478010660E-1	-9.874144414E-2
c_{3j} =	2.429792677E-3	-2.399191249E-4	8.609914011E-5	9.103543233E-5	-1.0621949 5E-4
c_{4j} =	3.369529095E-1	1.527309786E0	-5.499970381E-2	-1.796260694E-1	8.427113016E-3
c_{5j} =	2.743132044E1	8.456590718E0	2.193653708E0	1.798049075E0	-5.824153395E0
d1j =	-1.233381952E-2	-8.935182704E-4	-9.485435895E-4	-1.086932041E-3	9.394378173E-3
d2j =	-4.080446929E0	-1.866486940E0	-1.849817831E-1	-2.165400309E-1	9.219416997E-1
d3j =	1.098116450E-4	1.940932126E-5	8.195486081E-6	1.342279013E-5	-4.492395885E-5

1/ Numerical values are given in floating point notation, i.e., 2401.547 = 2.401547E3.

TABLE B-1 (cont.)

Numerical Values of Coefficients in Regression Model
Alum Coagulant
(soluble phosphorus in effluent only)

$$Y = b_o + c_o X_o + \sum_{i=1}^{5} a_i X_i + \sum_{i,k=1}^{5} a_{ik} X_i X_k + \sum_{i=2}^{5} c_i X_o^2 + d_1 X_2 X_5^2$$

$$+ d_2 X_3 X_5^2 + d_3 X_4 X_5^2$$

Y = concentration soluble phosphorus in effluent, mg/l
X_1 = column diameter, D, inches
X_2 = upflow velocity, U, ft/hr
X_3 = coagulant dose, Al, mg/l
X_4 = blanket depth, L, ft
X_5 = pH before coagulant addition
X_o = concentration of soluble phosphorus in influent, mg/l

b_o = 1.462988190E2
c_o = 3.692752427E-1

a_1 = 1.069903404E-1
a_2 = 3.278582248E1
a_3 = -1.768487898E0
a_4 = -6.782375143E0
a_5 = -3.818173316E1

a_{12} = -1.042707159E-2
a_{13} = 4.676882089E-4
a_{14} = 2.921856396E-2
a_{15} = -3.275133404E-2
a_{23} = 1.083331923E-3
a_{24} = -3.311203967E-2
a_{25} = -7.960189863E0
a_{34} = -1.227991728E-3
a_{35} = 4.323849665E-1
a_{45} = 1.736353973E0

c_2 = -3.841549079E-2
c_3 = 1.289097940E-4
c_4 = -5.218618145E-2
c_5 = 2.503469733E0

d_1 = 4.973385640E-1
d_2^1 = -2.754875542E-2
d_3^2 = -1.002247620E-1

TABLE B-2

Numerical Values of Coefficients in Regression Model
Ferric Chloride Coagulant

$$Y_j = b_{0j} + c_{0j}X_{0j} + \sum_{i=1}^{3} a_i X_i + c_{1j}X_1^2$$

Y_j = concentration of j in effluent, mg/l

X_{0j} = concentration of j in influent, mg/l

X_1 = upflow velocity, U, ft/hr

X_2 = ferric chloride dose, Fe, mg/l

X_3 = pH before coagulant addition

X_4 = (upflow velocity)^2

	Effluent Concentration Suspended Solids j = 1	Total Organic Carbon j = 2	Soluble Phosphorus j = 3	Total Phosphorus j = 4	Residual Fe^{+++} j = 5
b_0	300.849	439.909	-14.752	9.304	-79.880
c_0	0.300	0.593	0.058	0.420	-8.464
a_1	-63.180	-95.221	1.952	-1.770	20.024
a_2	-0.421	-0.183	-0.010	-0.018	0.016
a_3	15.210	14.314	0.655	0.345	-1.626
c_1	2.651	3.897	-0.078	0.068	-0.876

Table C

Data for Thickener Design

Sludge Subsidence Rates and Suspended Solids Concentrations

Settling Test No.	Settling Rate (SR) cm/min	Susp. Solids (SS) mg/l
A R	0.25	4,618
A R2	0.05	4,999
A R4--I	0.03	5,490
A R4--II	0.04	4,652
A R4--III	0.35	4,072
A R4--IV	0.40	3,602
A R5--I	0.40	3,781
A R5--II	0.46	3,849
A R5--III	0.49	2,010
A R5--IV	0.53	2,621
B a	1.69	1,559
B a'	1.75	1,559
B--I	0.16	5,222
B--II	0.49	4,736
B--III	0.57	4,054
B--IV	0.50	3,844
B--V	0.57	3,065
B--VI	0.82	2,394
B R--I	0.08	4,136
B R--II	0.44	3,488
B R--III	0.52	3,004
B R--IV	0.44	2,852
B R--V	0.[illegible]	2,244
B R2--VI	0.44	2,821
B R3--VII	3.14	669
B R3--VIII	2.54	847
B R3--IX	2.06	999
B S 1	0.43	3,070
B S 2	0.46	3,070

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16. Abstract

An experimental study of the application of a fluidized sludge blanket clarifier to the coagulation and separation of wastewater solids has been made to determine the effects of controlled process variables on the treatment achieved.

Experiments using alum and ferric chloride coagulants were carried out in 12- and 24-inch diameter columns by systematic variation of wastewater pH, coagulant dose, upflow fluid velocity, and blanket depth. The results were analyzed using regression analysis techniques, and empirical relationships were derived relating the variables to the removal of suspended solids, total organic carbon, phosphorus, and coagulant metal ions. The sludge production rate was also correlated empirically with the operating variables.

A study of the settling rates of discharged sludge and the fluidized blanket was made by direct observation.

17a. Descriptors

* Waste Treatment, * Coagulation, * Solids Contact Process, *Separation Techniques

17b. Identifiers

*Sludge Blanket, * Mathematical Model, Aluminum Sulfate, Ferric Sulfate, Activated Silica

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